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Department of Electronics
Lighting Unit

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Life cycle assessment in horticultural lighting

Thesis submitted for examination for the degree of Master of Science in Technology.
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AALTO UNIVERSITY
SCHOOL OF ELECTRICAL ENGINEERING Abstract of the Master's Thesis

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Abstract:
Environmental impacts such as global warming are affecting people and ecosystems negatively. In order to reduce environmental impacts, especially decision makers have to be informed of the consequences of the choices, which can escalate or curb the scale of environmental impacts. As the world population grows so does the demand for food and other crops. Greenhouse horticulture plays an important role in producing crops year around in places with unsuitable plant cultivation conditions. Such conditions make greenhouse horticulture dependent on supplemental artificial lighting. Horticultural lighting is the dominant cause of environmental impacts in greenhouses, which are heavily reliant on supplemental lighting. This thesis performs a comparative life cycle assessment experiment (LCA) to find out which lighting technology, light-emitting diode (LED) or high-pressure sodium (HPS), causes less environmental impacts in horticultural lighting. Another objective of this thesis is to act as a guide for greenhouse owners and people interested in LCA. The basics of plant biology, greenhouse growing, and life cycle assessment methodology are covered in order to acquaint the reader with horticultural lighting. After the theory and methodology part, the thesis performs the comparative LCA experiment to identify the scale of environmental impacts caused by the luminaires under study. This thesis confirmed the findings of previous light source LCAs: the luminaire use phase is the dominant cause for environmental impacts. Therefore, the negative environmental impacts can be reduced by choosing luminaires that use less electricity. The experiment found out that while producing one ton of cucumber seedlings LED luminaires used less electricity than HPS luminaires. Thus, LED lighting is environmentally friendlier than HPS lighting even though LED luminaire raw material production and manufacturing processes are more energy intensive than equivalent HPS luminaire processes. The environmental impacts of horticultural lighting can also be reduced significantly if countries switch to cleaner electricity production methods. The findings of this thesis should influence greenhouse owners and decision makers to consider the horticultural lighting options with the perspective LCA can provide.

Keywords: life cycle assessment, environmental impact, global warming, greenhouse, horticulture, lighting, light-emitting diode, high-pressure sodium

AALTO YLIOPISTO
SÄHKÖTEKNIIKAN KORKEAKOULU Diplomityön tiivistelmä

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Tiivistelmä:
Ympäristövaikutukset, kuten ilmastonmuutos, vaikuttavat ihmisiin ja ekosysteemeihin negatiivisesti. Jotta ympäristövaikutuksia voitaisiin vähentää, erityisesti päätöstentekijöiden tulee tiedostaa valinnat, jotka voivat kiihdyttää tai hillitä ympäristövaikutusten laajuutta. Väestönkasvun myötä ruokakasvien ja muiden viljelykasvien kysyntä kasvaa. Kasvihuoneviljelyn rooli viljelykasvien ympärivuotisessa tuotannossa korostuu alueilla, jotka eivät tarjoa kasvien kasvun kannalta sopivia olosuhteita. Kasvien kasvulle epäsuotuisat olosuhteet pakottavat kasvihuoneviljelijät turvautumaan täydentävään keinovalaistukseen. Valaistus on puutarhataloudessa suurin syy ympäristövaikutusten syntymiseen kasvihuoneissa, jotka ovat riippuvaisia täydentävästä valaistuksesta. Tämän diplomityön tavoitteena on tehdä vertaileva elinkaarianalyysi, jonka avulla selvitetään, kumpi valaistusteknologia, valodiodi (LED) vai suurpainenatrium (SPNa), aiheuttaa vähemmän ympäristövaikutuksia puutarhataloudessa. Diplomityön toisena tavoitteena on toimia oppaana kasvihuoneviljelijöille ja elinkaarianalyysistä kiinnostuneille. Kasvihuoneviljelyn ja kasvibiologian perusteet sekä elinkaarianalyysin metodologia käsitellään aluksi, jotta lukija voi tutustua valaistukseen puutarhataloudessa. Teorian ja metodien jälkeen diplomityössä käsitellään elinkaarianalyysi puutarhataloudessa käytettäville valaisimille. Diplomityö vahvisti aikaisempien elinkaarianalyysitutkimusten tulokset: valaisimen käyttövaihe on suurin syy ympäristövaikutusten syntymiseen. Näin ollen negatiivisia ympäristövaikutuksia voidaan vähentää valitsemalla valaisimet, jotka käyttävät vähemmän sähköä. Elinkaarianalyysin avulla selvisi, että tuottaessa tuhat kiloa kurkun taimia LED-valaisimet käyttivät vähemmän sähköä kuin SPNa-valaisimet. LED-valaistus on siis ympäristöystävällisempää kuin SPNa-valaistus vaikka LED-valaisimien raaka-ainetuotanto ja valmistus ovat energiaintensiivisempiä kuin vastaavat SPNa-valaisimien prosessit. Puutarhataloudessa käytettävän valaistuksen ympäristövaikutukset vähenevät huomattavasti, jos valtiot kehittävät sähköntuotantorakennettaan niin että se sisältää enemmän puhtaita sähkötuotantomuotoja. Tämän diplomityön tulokset hyödyttävät kasvihuoneviljelijöitä ja päätöksentekijöitä, jotka voivat harkita valaistuksen vaihtoehtoja myös elinkaarianalyysin näkökulmasta.

Avainsanat: elinkaarianalyysi, ympäristövaikutusten arviointi, ilmastonmuutos, kasvihuone, puutarhatalous, valaistus, valodiodi, suurpainenatrium

Forewords

I wish to thank my instructor, Doctor of Science Paulo Pinho, for his valuable guidance during this thesis. I also want to thank my supervisor, Professor Liisa Halonen, for the opportunity to work at Lighting Unit. This thesis would not have been possible without the help and faith in me from both of you.

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Espoo, December 9th 2013

Michael Grigoriadis

Table of contents

List of abbreviations and symbols

Abbreviations

CEN	European commission of standardization
CFL	Compact fluorescent lamp
CHP	Combined heat and power
CIE	International Commission on Illumination
GLS	General lighting service incandescent lamp
GWh	Gigawatt-hour
HPS	High-pressure sodium
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LED	Light-emitting diode
kWh	Kilowatt hour
lm	Lumen
lmh	Lumen-hour
lx	Lux
Mlmh	Mega lumen-hour
Molh	Mole-hour
nm	Nanometer
PAR	Photosynthetically active radiation
PPF	Photosynthetic photon flux
PPFD	Photosynthetic photon flux density

Symbols

°C	Celsius degrade
CO_2	Carbon dioxide
$C_6H_{12}O_6$	Sugar glucose
H_2O	Water
O_2	Oxygen
E_p	Photosynthetic photon flux density (PPFD)
E_e	Irradiance
λ	Wavelength
N_A	Avogadro's number
h	Planck's constant
c	Speed of light in a vacuum
μmol	Micromole
N_2O	Nitrous oxide
CH_4	Methane

1 Introduction

1.1 Background

The growing world population is presenting a huge challenge for crop production with arable land shrinking rapidly. Conventional agriculture by itself cannot continue to sustain food and other crops production. Crops production must become more efficient in terms of land use in order to satisfy most importantly the growing demand for food.

Greenhouse horticulture offers a solution for the arable land shortage by providing new places to grow crops. Greenhouses are essential in crop cultivation in places where conventional agriculture cannot provide year around production. Furthermore, greenhouses are very efficient in terms of land usage compared to agriculture.

However, horticulture has its own challenges. The challenge that will be focused on in this thesis is the environmental impacts of horticultural lighting. The largest contributor for these environmental impacts is artificial lighting. Natural light is the main light source for greenhouses, but when it is not available, natural light can be supplemented with artificial light sources. These light sources require large amounts of electricity to operate.

There have been no significant life cycle assessment (LCA) studies in horticultural lighting before. Thus, this thesis is important for two reasons. Firstly, it promotes the sustainable crops production. Secondly, it establishes guidelines and a common ground to discuss the principles of how to conduct horticultural LCA studies in the future.

1.2 Aim of the work

The aim of the work is twofold consisting of the objective of the thesis and the goal of the LCA experiment. The objective of this thesis is to act as a guide for assessing the environmental impacts of artificial light sources used in horticultural lighting. The thesis aims to reach this objective by first explaining and then utilizing the LCA methodology to the reader. The experiment follows closely the LCA methodology. The LCA experiment is supposed to act as a detailed step by step example of a simple LCA, which can be improved or used as a reference in future LCAs. The goal of the LCA experiment is to identify which lighting option, LED or HPS, is environmentally friendlier in cucumber seedling production.

1.3 Structure of the thesis

The structure of the thesis follows the standard guideline for such work: introduction, theory, methods, experiment, and conclusion. The theory part covers the background of common artificial light sources used today in greenhouse horticulture. After the theory part, the thesis introduces the LCA methodology. Next, the thesis performs the comparative horticultural lighting LCA experiment. Finally, the thesis will conclude how well the aim of the work has been reached and suggest further research possibilities.

2 Horticultural lighting

The objective of this chapter is to provide background information in plant biology and greenhouse horticulture. First in discussion are plant biology and its interactions with light. After that, the thesis covers greenhouse horticulture and artificial light sources in horticultural lighting.

2.1 Plant interaction with light

The relationship between plants and light is diverse. Plants grow and adjust to changing conditions using energy and information provided by lighting [1]. Light is the primary source of energy for plants. Light also enables plants to gather information from the surrounding environment. Furthermore, certain wavelengths of light have a positive effect on plant immunology proven by field testing with tomato and cucumber [2].

Plants have three different photosystems which function is to utilize light: photosynthetic system, phytochromatic system, and cryptochromatic system [1]. Photosynthetic system is responsible for converting photons into chemical energy which is required for a plant to grow. Phytochromatic and cryptochromatic systems provide information of the surroundings to the plant by monitoring different wavelengths of red and blue respectively.

Light interacts with plants in several different processes from which photoperiodism, phototropism, photomorphogenesis, and photosynthesis are the most essential [1]. These processes are affected by the parameters of light such as quantity, quality, direction, and periodicity. Photoperiodism regulates the circadian rhythm in plants; phototropism regulates the growth direction of a plant towards or away from light; and photomorphogenesis regulates the appearance and form of a plant depending on the quality of light.

2.1.1 Optical window for plants

Plants are able to utilize energy from wavelengths in an optical window ranging from around 300 nm to 1000 nm. However, the optical window officially used for plants is based on photosynthetically active radiation (PAR) wavelength region between 400 nm and 700 nm defined by CIE, the International Commission on Illumination. The PAR area contains most of the wavelengths important for the photosynthetic system. Longer wavelengths outside the PAR range are mostly unable to carry enough energy to impact the photochemical processes in plants and lower wavelengths contain so much energy that they destroy plant photoreceptors [1]. Figure 2.1 illustrates that plant photoreceptors are most sensitive in the absorption peaks 430 nm (blue light) and 660 nm (red light). Chlorophylls a and b are the most important photoreceptors. Chlorophyll b absorbs the incoming photons and passes them to chlorophyll a which is mostly responsible for the assimilation of chemical energy. The photosynthetic system utilizes the full optical window whereas phytochromatic and cryptochromatic systems responsible for information gathering operate on areas of blue, red, and far-red wavelengths [1].

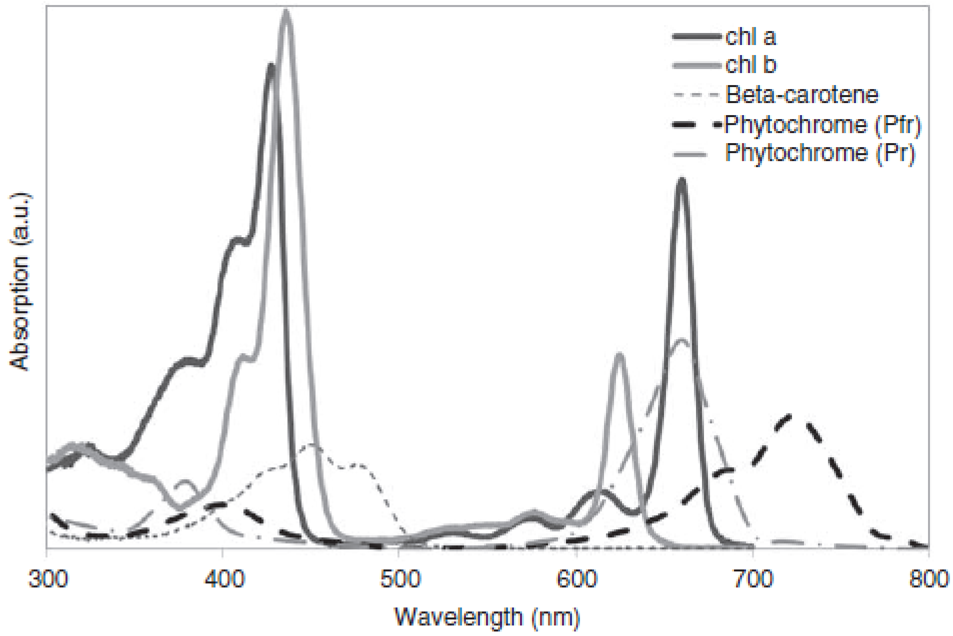

Figure 2.1. Absorption spectra of most common plant photoreceptors. [3]

2.1.2 Photosynthesis

Photosynthesis is a process where inorganic matter is converted into organic compounds. The most notable photosynthetic process in plant physiology is the photosynthesis of carbon dioxide, where a plant converts carbon dioxide and water into carbohydrates by using light energy to run the process. Sugar glucose is the typical output in this process and oxygen the waste product. Photosynthesis also requires a suitable temperature to operate. The optimal temperature for most plants is around +20 °C. The simplified equation for photosynthesis is as follows:

$$6\,CO_2 + 6\,H_2O \xrightarrow{light\ energy} C_6H_{12}O_6 + 6\,O_2 \tag{1}$$

where

CO_2 is carbon dioxide
H_2O is water
$C_6H_{12}O_6$ is sugar glucose
O_2 is oxygen. [1]

Light energy is essentially radiation that has characteristics from both electromagnetic wave and particle. Radiation interacts as a photon particle with plants. These photons are captured by plants photoreceptors and converted into chemical energy. Photosynthesis happens mainly in plant leaves where most of the photoreceptors are situated. Photosynthesis is more efficient when the spectrum of the incoming radiation is closer to photoreceptors absorption spectra. Wavelengths in the red area are the most essential for photosynthesis. Other important wavelengths include blue and far-red. The perfect spectrum varies from plant to plant, but generally it should consist of 70 – 90 % red and 10 – 30 % blue wavelengths depending on plant. [4] Photosynthesis has little use for green and yellow radiation.

2.1.3 Photomorphogenesis

Photomorphogenesis is plant development, which results from light. This development consists of many activities, which expand plant mass such as stem elongation, leaf expansion, and root spreading. Photomorphogenesis depends on several different photoreceptors in both blue/UV-A and red/far-red wavelength areas. The red/far-red wavelength area is used by photoreceptors called phytochromes. The blue/UV-A area is associated with photoreceptors such as cryptochrome, phototropin and other UV-specific photoreceptors. [1]

2.1.4 Phototropism

The direction of light affects the amount of photons falling on plant leaves. Plants respond to the incoming direction of light by growing towards the light or away from it depending on the deficiency or surplus of light. This behavior is known as phototropism. The response is positive if the plant grows towards light and negative if it shies away from it. Typically plant parts above surface such as leaves tend to have a positive phototropic response whereas underground parts have a negative phototropic response. The color of the light also affects the growth direction of plants. Especially blue and other low wavelength radiation is associated with phototropism. Phototropism is controlled by the blue light photoreceptor phototropin. [1]

2.1.5 Photoperiodism

Aside from spectrum, direction, and quantity of light, the periodicity of light also affects plant growth. Plants use short-term and long-term periodicity of light as a biological clock to determine the circadian rhythm and seasons respectively. During the day cycle, plants are active and gather light. During the night cycle, plants do not gather light and therefore lower their leaves to save energy and focus their energy in growing. Plants identify the time of the day by assessing the red to far-red light ratio and the amount of blue light. A change in periodicity of light is responsible for triggering a transition from vegetative to flowering growth state. The change can also impact other stages in plant development such as leaf fall off, breakout of new buds, and bulb formation. [1]

2.1.6 Quantification of light

Plant interaction with light differs from human eye interaction with light. Therefore, light cannot be quantified by units designed for human eye such as lumens. Since plants use photons in processes such as photosynthesis and photomorphogenesis, they require a metric that is able to express light energy in photons. The recommended metric for quantifying light falling on plant surface is photosynthetic photon flux density (PPFD). In literature, PPFD is confusingly sometimes referred to as photosynthetic photon flux (PPF) and vice versa [4]. PPFD measures the amount of photons per unit area and per time unit falling on a surface. It can be calculated so that it includes photons from all wavelengths, but for plants it is sensible to limit the wavelength range to PAR area or extended PAR area. Photons are measured in micromoles.

The energy content of a photon varies depending on wavelength. In plant processes, every photon is treated equal regardless of the amount of energy it contains. According to the Stark-Einstein law, any absorbed photon is able to cause a chemical or physical reaction. For example, in photosynthesis, the efficiency of the process is dependent on the amount of photons, not the amount of energy in a photon. A plant is never able to utilize the total energy of an absorbed photon. Therefore, it emits a portion of the total energy as heat to the environment. If a light source is too powerful, the plant processes saturate and cannot use the incoming photons. The surplus photons are converted to heat, which in high amounts can damage the plant. The ideal PPFD value varies between plants and is dependent on the spectral distribution of the light source. [1]

Irradiance is another way to quantify the amount of light in an area. It measures the power of electromagnetic radiation per unit area (i.e., radiative flux) falling on a surface. The equation to calculate irradiance varies depending on the optics of the light source. PPFD is generally measured with a quantum meter, but it is also possible to measure irradiance and then convert it to PPFD. The following equation can convert irradiance into PPFD if the spectral distribution of the light source is known.

$$E_p = \int_{\lambda=400nm}^{700nm} \left(\frac{\lambda}{N_A * h * c} E_e(\lambda) \right) d\lambda \cong \sum_{\lambda=400nm}^{700nm} \frac{\lambda}{N * h * c} E_{e,\lambda} \qquad (2)$$

where

E_p is photosynthetic photon flux density (PPFD) $(\frac{\mu mol}{m^2 * s})$
E_e is irradiance $(\frac{W}{m^2})$
λ is wavelength of radiation (nm)
N_A is Avogadro's number $(6.022 * 10^{23} \frac{1}{mol})$
h is Planck's constant $(6.626 * 10^{-34} J * s)$
c is the speed of light in a vacuum $\left(2.998 * 10^{8} \frac{m}{s}\right)$. [5]

2.2 Greenhouse horticulture

Greenhouse horticulture in essence is plant cultivation inside a glass or plastic structure. Horticulture is a science focusing on efficient plant cultivation with the purpose of producing quality crops for food and other uses such as medicine and landscaping. Greenhouses are structures that have been developed to improve horticulture and crop production even further. Together, they form greenhouse horticulture that enables year around crop production in areas where it would otherwise be harder or even impossible.

The history of greenhouse horticulture dates back to Roman times. In order to provide vegetables for the emperor to enjoy year around, the gardeners resolved to plant vegetables in wheeled carts. The carts were kept in the sun during the day and taken back by night to protect them from cold. Instead of glass or plastic, the gardeners used oiled cloth and transparent minerals to cover the vegetable cart greenhouses. Since then, greenhouse horticulture has evolved significantly. [6]

2.2.1 Modern greenhouses

Greenhouses vary in size, shape, and technology depending on application and geographical area. The size of a huge commercial greenhouse can be many hectares whereas the smallest greenhouses are so small they only hold few plants. Greenhouses in northern latitudes are smaller and have more climate control tools than greenhouses in geographical areas, which have no need for heavy climate control. The basic prerequisite for crop production is sufficient lighting, carbon dioxide, water, and temperature. Climate control tools can significantly improve these conditions favorable to plants. Greenhouses also provide protection from negative effects of the environment such as wind, excessive rain, and hail. In arid climate, greenhouses protect plants from excess heat and water loss by operating as cooling buildings with appropriate technology.

Aside from climate control, efficient plant production requires sophisticated production methods. Plants need a growth medium, which can offer stable pH, nutrients, and protection. Soil is still the most used growth medium utilized in greenhouse horticulture to this day. Soil can be fertilized with manure or chemical fertilization solutions. Plants can also be grown hydroponically without the use of soil. Hydroponics systems are fertilized using fertigation, which is dissolving the nutrients in water and distributing them by drip irrigation. Aeroponics is a growing method that does not require any growing medium at all. In Aeroponics, nutrients are distributed in various ways with misty air as the most common method. Aeroponics is rarely used in commercial greenhouses. Initial investment cost of advanced production methods are higher than in conventional greenhouse horticulture with soil. However, fertilization is more difficult in soil than in water based methods. In addition, soil is also more prone to insects and diseases than hydro- or aeroponics if left unattended [7].

Transparent materials used in greenhouse walls and roof prevent heat from escaping. Air inside a greenhouse is warmed by convection effect, which partially retains incoming thermal energy. Plants also produce heat due to their inability to utilize all the energy of a photon in photosynthesis. However, this effect is still minor compared to convection. Glass is the earliest material used in greenhouse horticulture that is still in use today. It is mainly used in Europe and North America. Recently, polyethylene has surpassed glass as the dominant building material in greenhouses. Polyethylene covered greenhouses lose less heat compared to glass greenhouses [8]. Polyethylene is heavily favored over glass in Asia and the Mediterranean area. Other building materials for greenhouses include acryl, fiberglass, polycarbonate, and polyvinyl chloride, but these are rarely used due to high cost compared to polyethylene.

Countries that regard greenhouse horticulture as an important industry also facilitate and invest in horticulture research institutions. The Netherlands is considered as the country with most advanced technological and practical expertise in horticulture due to their research institutions and large horticultural industry. Other notable countries in horticultural research are the United Kingdom, North America, Japan, Spain, and Israel.

2.2.2 Artificial light sources

Sun is not able to provide enough lighting for plant cultivation in dark seasons especially in the northern latitudes. Artificial lighting is needed to provide supplemental lighting when light from the sun is not enough. The first reported use of artificial lighting in greenhouse horticulture is from year 1861 even before incandescent lamp (GLS) was invented [9]. This thesis focuses on the most common artificial light sources in greenhouse horticulture, which are high-pressure sodium (HPS) and light-emitting diode (LED) luminaires. Other artificial light sources include ceramic metal halide, compact fluorescent (CFL), and sulfur lamps. Artificial light sources can be compared with a variety of criteria such as cost, quality of light, efficiency, optics, and environmental impacts.

Horticultural lighting is responsible for most of the energy usage in greenhouses [3]. One of the greatest challenges in greenhouse horticulture is to reduce energy usage in order to reduce environmental impacts. LED luminaires are best suited to help in this challenge due to their low energy consumption. On the other hand, HPS luminaires require higher power than LED luminaires to provide desired lighting to plants. Higher power results in more waste heat. Generally, waste heat is negative, but in cold climates waste heat actually helps to warm greenhouses, which reduces the amount of additional heating needed to sustain greenhouse temperature at a sufficient level.

LED technology offers improved control possibilities over HPS technology. LED luminaires offer the possibility to customize their installation height or placement, which enables more optimized light distribution and multi-layer growing. LEDs can operate as side lighting and they can be placed near the plants due to small heat radiation. In addition, a control system can make an LED luminaire consisting of many different dies with a narrow spectral area more adjustable than an HPS luminaire in terms of quantity and spectrum of light.

LED luminaires contain fewer materials that cause environmental impacts compared to HPS lamps, for example, LEDs contain no mercury whereas HPS lamps contain mercury and lead. However, the manufacturing process of LED luminaires is more energy intensive than HPS luminaires. [10]

The spectrum of light from LED luminaires is more optimal for plants compared to the spectrum of HPS luminaires. The wavelength distribution in HPS luminaires is heavily focused on red wavelengths, which is problematic due the low red to far-red ratio and low amount of blue light. These wavelengths that can be incorporated easily to LEDs are missing in HPS lamps. This leads to abnormal photomorphogenesis distorting the length of leaves and stem making plants parts longer, but also thinner [11].

In the future, LED luminaires will to surpass the dominance of HPS luminaires in horticultural lighting. This is based on the Haitz's law, which states that LED increases in light output by a factor of 20 while costs fall by a factor of ten, both over ten years [12]. The development of light output can be seen in Figure 2.2. HPS luminaires are popular due to their low cost, but as LED technology keeps improving and the LED luminaires become more popular, the prices of LEDs will drop. LEDs have already increased their share in artificial lighting from almost zero to 9 % in just a few years. According to estimations, LEDs will account for 45 % of general lighting in 2016 and 70 % by year 2020 [13].

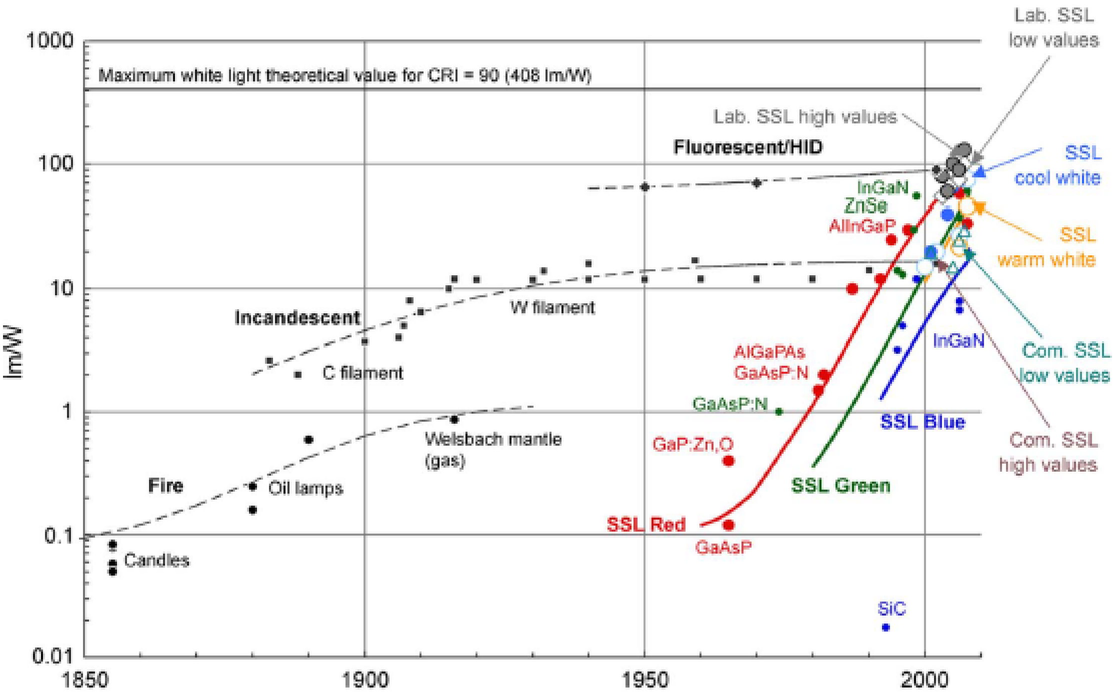

Figure 2.2. The development trends for different lighting technologies. The Fluorescent/HID curve is stagnant whereas the curves of different colored LED technologies are rising steadily. [14]

2.3 Growth experiment

The practical part of this thesis is based on a cucumber (Cucumis sativus) seedling growth experiment conducted in Piikkiö, Finland by MTT (see Appendix A). The light sources used in the Piikkiö experiment were:

1. LED luminaire #7
2. LED luminaire #8
3. A generic 250 W HPS lamp with a dated lamp holder and a ballast
4. Conventional daylight.

The growth experiment was designed so that PPFD at the surface of growth medium was 130 µmol/m^2/s except in the natural light treatment. The amount of luminaires needed to fulfill this requirement varied between treatments. Treatments 1 and 3 required two luminaires. Treatment 2 required three luminaires.

The lighting period was 20 h / 4 h (day/night). Temperature in the greenhouse was 25 °C / 22 °C (day/night). Plants were fertilized automatically with ordinary fertigation solution once a day. The experiment lasted for 21 days.

Results of the growth experiment are based on the means of seven plants per treatment with standard error. Fresh weight for 1st luminaire was 38.99 g/plant, 63.27 g/plant for 2nd luminaire, 88.67 g/plant for HPS, and 10.38 g/plant for the daylight treatment.

From the results, it can be concluded that the HPS luminaire produces over 40 % more yield in cucumber seedlings than the best LED luminaire in 21 days with similar conditions. One reason for such a high discrepancy in yield could be explained by temperature. In other growth experiments conducted by non-professionals, the optimal temperature for cucumber seedlings is reported to be closer to 28 °C / 22 °C. Depending on the height of lighting fixtures, ventilation of growth room, and position of thermometer, the actual temperature in HPS treatment is likely to be higher than in the LED treatments. Thus, the HPS treatment yield is far superior to the LED treatments. Second reason might be that the spectrum from the HPS luminaire is more beneficial for cucumber seedling growth than the spectra from LED luminaires. Nevertheless, the results and luminaire measurements from this growth experiment will be used as a basis for the LCA experiment of this thesis without any changes.

2.4 Conclusion

In this chapter, the topics of discussion have been the principles of horticultural lighting, plant interaction with light, and greenhouse horticulture. Horticultural lighting is a field of technology that combines elements from both horticulture and illumination.

Plant interaction with light is an essential mechanism that sustains plants ability to live. Light is need for the energy it provides for the processes that drive plant growth. The most important of these processes are photosynthesis and photomorphogenesis. Photosynthesis is a process which allows plants to convert energy for their use. Photomorphogenesis is a process that uses most of the chemical energy gained from photosynthesis. Other processes give information of the surrounding environment to the plant. All these processes rely on chlorophylls that act as receptors of light. Different chlorophylls are responsible for different processes and sensitive to varying wavelength areas of light spectrum. The amount of light available for chlorophylls is calculated by a metric called photosynthetic photon flux density (PPFD) that is based on photons that fall on photosynthetically active radiation (PAR) area.

Greenhouse horticulture is an activity that is dependent on horticultural lighting. Sun provides a large portion of this lighting, but since greenhouses have to operate year around to satisfy the demand for food and other crops, artificial light sources are needed to provide supplemental lighting to greenhouses. Modern greenhouses with advanced technology are the future of food production. Greenhouses of varying size and technology can grow crops with multiple production methods such as conventional soil growing or soilless hydroponics. The most common artificial light sources in horticultural lighting are light-emitting diode (LED) and high-pressure sodium (HPS) luminaires. Even though HPS is still the dominant technology, the fast improvement of LED technology offers promising future aspects in greenhouse horticulture.

Finally, conditions and results of a growth experiment that was conducted in Piikkiö, Finland are discussed. This growth experiment is used to determine the amount of luminaires needed in the life cycle analysis experiment of this thesis.

3 Life cycle assessment methodology

This chapter provides an overview of how to perform an LCA and discusses the LCA methodology on a general level. This introduction to LCA is useful for a person with no previous experience with LCA, because it helps to understand the basics of LCA. Later, this thesis will give guidelines and examples on how to perform an LCA for light sources used in horticultural lighting. By going through the basics of the methods used in LCA, the reader will understand the experiment part of this thesis more easily.

The LCA method is defined in standards ISO 14040 and ISO 14044. ISO 14040 states the principles and framework for LCA. ISO 14044 defines the requirements and details of how to conduct an LCA. This thesis follows the guidelines provided in these standards. The standards also provide the framework that this thesis will be using (see Figure 3.1).

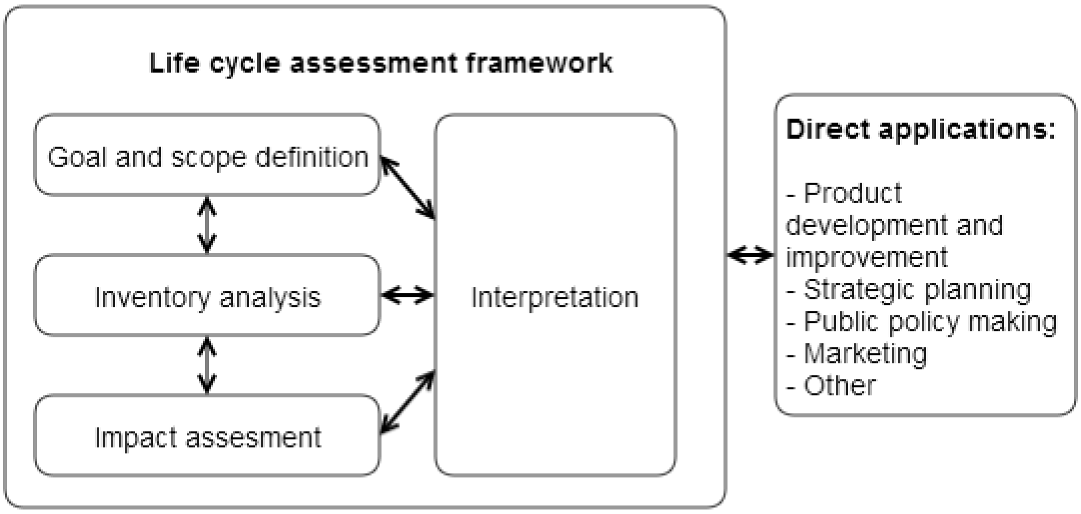

Figure 3.1. The basic LCA framework. Adapted from [15].

Conducting an LCA has numerous benefits. Humans are polluting the environment constantly, but often due to lack of information. LCA can help in:

1. Identifying the environmental effects caused by a product. Thus, enabling product development and improvement aiming for a less polluting product.
2. Strategic planning as a tool for evaluating the environmental impacts of a product.
3. Providing information about different environmental opportunities for policy makers to decide.
4. Selecting or discovering relevant methods or indicators for improving measurement techniques.
5. Marketing of a greener product - possibly with an ecolabel.

LCA methodology is composed of four phases:

1. *Goal and scope* defines the depth and focus of the study.
2. *Life cycle inventory analysis* (LCI) is used to collect, validate and manage data.
3. *Life cycle impact assessment* (LCIA) uses the results of LCI to evaluate the magnitude of environmental impacts.
4. *Interpretation* is for evaluating and interpreting the previous phases.

LCA can be performed in various ways. There are three common types of quantitative LCA studies:

1. *Stand-alone LCA* is used to study a single product. A stand-alone study can identify the activities which cause the greatest environmental impact. This the most common approach to perform LCA studies in industry.
2. *LCA of the accounting type* are comparative and retrospective in nature. Accounting type LCAs can, for example, inform purchasers of the environmental impacts of each option.
3. *LCA of the change-oriented type* are comparative and prospective in nature. Change-oriented LCAs are best suited for product development.

LCA is used as a tool to study the environmental impacts caused during the life cycle of a product. The life cycle of a product begins from resource extraction or “cradle”, continues to material and product production “gate”, and ends in waste management or “grave”. In comparison, an LCA has starting and ending points depending on how the study is defined. A cradle-to-grave study is more comprehensive than an otherwise similarly defined cradle-to-gate study.

LCA is mainly associated with environmental issues. Therefore, social and economic aspects are not relevant for an ordinary LCA study. Social and economic aspects are part of “social LCA” and “life cycle costing”, respectively. These studies should not be mixed with a regular LCA. However, social and economic aspects can sometimes be defined as environmental categories even in a regular LCA [15].

3.1 Goal and scope

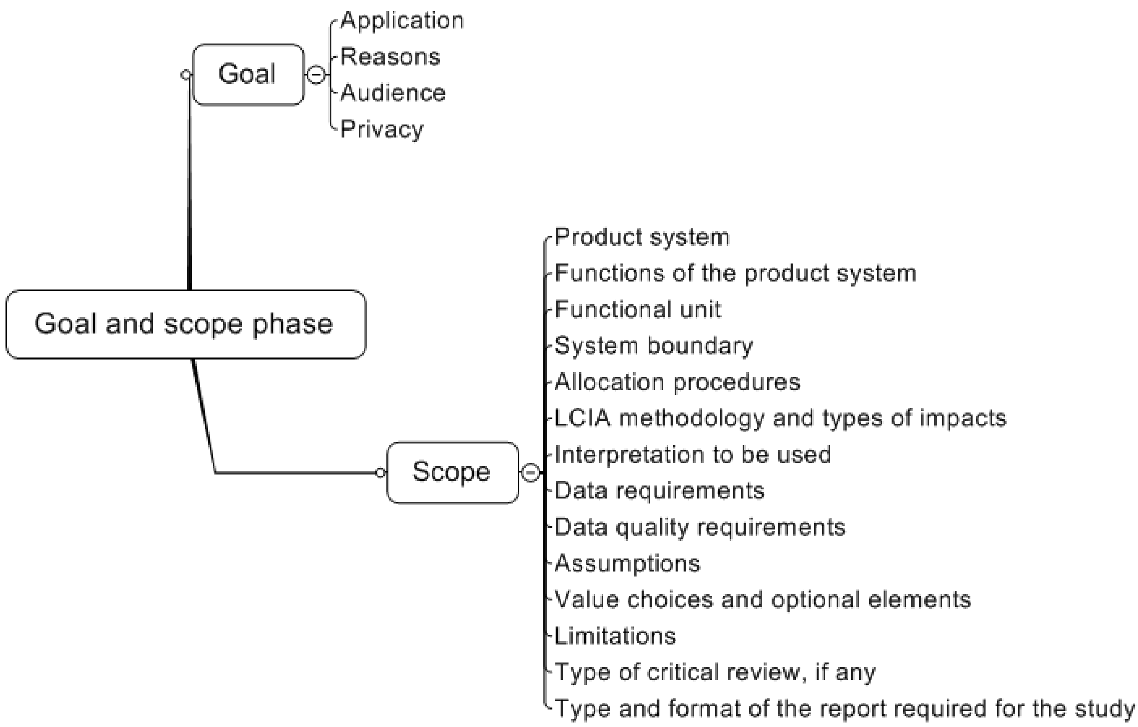

Figure 3.2. An overview of the goal and scope phase. [16]

Defining the goal and scope of an LCA involves numerous elements as can be seen in Figure 3.2. It is common that many of these elements are considered, but not documented in LCA reports and articles. Still, all these elements should be defined according to the standard. Studies often omit elements from the goal and scope phase, but define them in later phases of the study.

LCAs begin with the goal and scope phase. A goal must state the intended application, reason for carrying out the study, intended audience of the study, and degree of privacy of the study. The purpose of the goal is to give the practitioner of the LCA a direction to aim the study. As stated previously, there are many possibilities to conduct an LCA. That is why it is important to identify the questions that the LCA will be answering. The answers to these questions will be vague and poor in quality unless the scope of the study is well defined. A clearly-defined scope is as important foundation for an LCA study as is the goal. Most importantly, the scope establishes boundaries for the study.

3.1.1 Scope terminology

A *product system* is a combination of *unit processes*. They represent different steps in the life cycle of a product such as material production, use, and transport. The unit processes consist of *resource flows* referred to as *inputs* and *outputs*. Resource flow can also be expressed as *reference flow*, which is measured in *functional units*. Usually, the practitioner drafts the first rough version of the flow model representing the product system when defining the product system such as in Figure 3.3.

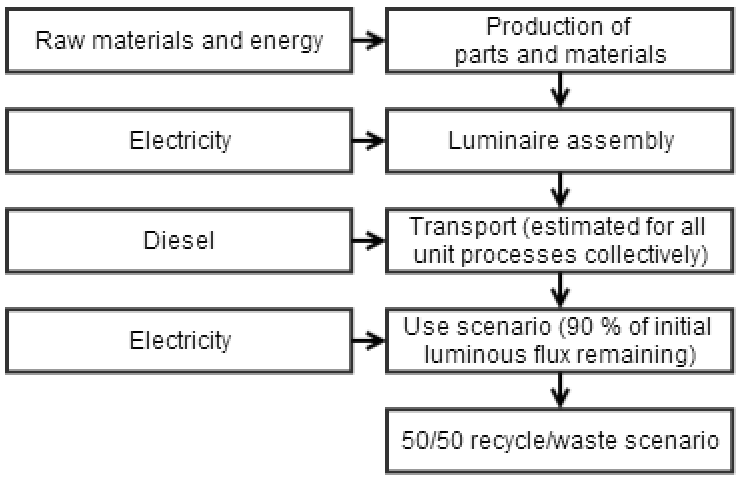

Figure 3.3. A basic flow model for an LED or HPS luminaire used in horticultural lighting.

A *functional unit* is the reference point where the inputs and outputs are related to. A well-chosen functional unit enables different products of the same type to be compared. A functional unit should be chosen so that it can normalize the inputs and outputs to ensure the comparability of the LCA study. An LCA study is relative to the functional unit. It is possible to receive totally different results with even similar products depending on the functional unit used. This is why it is important to choose a common, unbiased and fair functional unit for every product type. Possible functional units for horticultural lighting will be discussed in the next sub chapter.

The *system boundaries* of a product system limit the amount of detail in a study. System boundaries prevent the LCA study from including every single irrelevant unit process. The selection of system boundaries is based on the questions the LCA is trying to answer. This makes the selection a subjective choice of the LCA practitioner. The selected system boundaries have to be based on cut-off criteria such as environmental significance of inputs and outputs, weight, or price. Depending on the scale of the study, horticultural lighting LCAs can exclude or include other product systems such as fertilizers that affect the crop, which is the end product. The following boundaries appear commonly on LCA studies:

1. Starting point of a product system. This determines the boundary between the technological system and nature.
2. Geographical area. An LCA study is bound to the geographical area where it is performed. This can cause large variations in results depending on the subject of study.
3. Time-related boundaries. Data collection can be performed only through a limited time span. Furthermore, the freshness of the data is a boundary dependent on time.

Allocation as defined in the ISO 14040 standard is "partitioning of the inputs and outputs between the product being studied and other product systems" [16]. An allocation problem is present if a unit process has multiple inputs, multiple outputs, or the unit processes form an open loop recycling product system. In such case the inputs or outputs can be difficult to partition between the unit processes. A basic horticultural lighting product system does not have allocation problems. However, there are three common solutions to a possible allocation problem:

1. *Increasing the level of detail of the product system* can help to allocate multiple inputs and outputs, but it may not always be enough to solve the problem and increasing the detail level means more work in the form of additional data collection.
2. *Allocation through partitioning* allows an input or output that is related to multiple unit processes can be divided between them (e.g. if the unit process "product manufacturing" produces excess heat then the unit process "raw material acquisition" will have a smaller environmental impact, because the energy output that is gained from product production is subtracted from the energy input of raw material acquisition).
3. In *system expansion* the input or output is related to a different product system (e.g. excess heat can be related to an additional unit process "production of alternative fuel").

Data requirements and *data quality requirements* convey the credibility of the study. Data quality is defined as "characteristics of data that relate to their ability to satisfy stated requirements" [16]. The requirements have been listed in the ISO 14044 standard. These requirements can be sorted under the headings relevance, reliability and accessibility as can be seen in Table 3.1. Time-related coverage and geographical coverage indicate how relevant the study is by assessing the recentness and the geographical requirements of the data. Technology coverage assesses if the type of technology and the data collected from its research is relevant to the study. Completeness and representativeness reveal if the study has used sufficient amount of data so that the data can sustain a sensitivity analysis. Precision is the opposite of uncertainty of the information, but still both of these aspects have to be considered when assessing data quality. The reliability of the data also depends on consistency and the sources of data. Studies that are public should be transparent so that they may be easily accessed by the public. Such studies should be consistent with other similar studies by allowing reproduction and comparability of the study.

Table 3.1. Requirements of data and data quality. [17]

Relevance	Reliability	Accessibility
Time-related coverage	Precision	Reproducibility
Geographical coverage	Consistency	Consistency
Technology coverage		
Completeness		
Representativeness		

Assumptions and *limitations* in an LCA study are practically inevitable. It is important to state these factors, because it makes the study clearer to write and read when they are acknowledged. The goal and scope should include all the major assumptions such as the technology used in system expansion. Smaller assumptions are too small to mention in the goal definition phase for practical reasons. Same rules apply to limitations. Limitations such as time, geography or data collection problems are good to mention in the goal and definition phase.

There are three types of *critical reviews*: internal review, external expert review, and review by interested parties. Including the interested parties in critical reviews increases the chance that the LCA's conclusions and recommendations will be taken into account in decision making. Critical review is mandatory when a public study is intended to do a comparative assertion. Even if the study is not a public comparative assertion, a critical review of any type is always preferred to no critical review at all, because it improves the credibility and quality of a study. An optional interactive internal or external peer review is useful for helping the practitioner make a quality study. A peer review addresses, for example, the assessment of scope, data acquisition methods, assumptions, and results.

Lastly, the *type and format of the report required* for the study has to be stated. The purpose of a report is to communicate the results in an understandable fashion. The basis of a report document consists of: administrative information, goal and scope definition, LCI, LCIA, interpretation, and critical review if any.

After the goal and scope have been defined, they must be followed consistently throughout the study. However, the goal and scope may change during the process of the study. Discovering unexpected new information can affect the previous phases of the study [18]. This iterative feature of the LCA methodology makes it harder to conduct than a straightforward environmental assessment methodology.

3.1.2 Functional units in horticultural lighting

There are a few functional units applicable for the LCA experiment in this thesis. Advantages and limitations of these functional units will be discussed here. The functional unit is chosen based on function of the product system. The function of horticultural lighting is to provide photons for plants in order for the plants to grow. Thus, the functional unit has to have a reference to yield. This differs from lighting LCAs, which focus on illumination for people. Commonly used functional units in light source LCAs include lifetime hours, energy consumption, and lumen-hours.

Luminous flux (lm) is a measure, which depicts how much visible light a light source radiates in total. One study has used equivalent luminous flux 8000 h as a functional unit, because it is the lifetime of an 18 W CFL, which they compared with a 100 W GLS [19]. Another study used 345 - 420 lm during 25000 hours as a functional unit [20]. Yet another study, which compared a 13 W CFL and a 60 W GLS, used 500 - 900 lm during 10 000 hours as a functional unit [21]. As can be seen, the functional units can be quite difficult to comprehend at first. The functional units have two similar components in these studies, a required amount of lumens and time frame. When a lamp is too old it will not be able to produce the required amount of lumens and is discarded. Luminous flux is a suitable functional unit for conventional illumination. However, for a horticultural lighting LCA, luminous flux is not an accurate functional unit. Photosynthesis requires photons from a wide spectral range, whereas lumens are just photons that are in the range of light visible to human eye.

Illuminance (lm/m^2 or lx) measures the luminous flux that falls on an area. Illuminance has not been used before in any notable LCA. The reason for this is that it cannot be used as a reference for the function of a product system. There is not a total amount of luxes a lamp can produce, because luxes are dependent on area and installation height. The flows cannot be based on a fickle variable. Even if the area and installation height were constants there is another problem with illuminance. A functional unit cannot be a measure, which is divided by any factor such as square meter, kilowatts, kilograms, and time. The reason for this is the same as mentioned before: such measure cannot be used as a reference for the function of a product system. For example, a greenhouse produces a yield during its lifetime, which is a reference product. Yield per kilowatt is the efficiency a greenhouse produces the yield. Efficiency is not a reference product. Thus, yield per kilowatt is not a functional unit, whereas yield is one.

Photosynthetic photon flux (µmol/s) and *photosynthetic photon flux density* (µmol/m^2/s) are both metrics that, in plant biology, express the amount of photons falling on leaf surface per time unit and on the case of density, per unit area as well. Both are widely used metrics by plant biologists. However, neither can be used as a functional unit, for the same reason luxes cannot be used as a functional unit. PPF and PPFD both measure efficiency, which is not a reference flow. In addition, PPF and PPFD are affected by external factors such as distance from plants and spectral distribution of light.

Lifetime hour (h) is the amount of hours a lamp can illuminate before it becomes obsolete due to luminous flux dropping below 70 % of the initial level. Lifetime hour has been used as functional unit in three LCAs. The first compared 60 W GLS and 15 W CFL, choosing 10000 h as functional unit [22]. The second LCA studied various lamps and used 1 h as functional unit [23]. The third study assessed the most beneficial street lighting alternative equivalent to 150 W HPS lamp and chose a functional unit of 100000 h [24]. Lifetime hour is a simple functional unit that is easy to understand, making the function of product system (i.e., lamp) to just last as long as possible. Lifetime hour is not a good functional unit if the product system is more complex though as in horticultural lighting. Lifetime hour can be used as an additional requirement in a functional unit, accompanying luminous flux as a separate unit (345 - 420 lm during 25000 h) or a compound unit (1 Mlmh).

Lumen-hour (lmh) is a unit measuring the amount of lumens a light source produces in an hour. Lumen-hour is the most common functional unit used in light source LCA studies. 1 Mlmh has been used as functional unit in five different studies [10, 25-27]. The U.S Department for Energy made a study comparing notable light source LCAs and used 20 Mlmh as the functional unit in their LCA experiment [28]. Lumen-hour is derived from multiplying lumens by lifetime hours and by the number of lamps. For example, a 900 lumen GLS with a lifetime of 1000 hours must be replaced 22 times to produce 20 Mlmh, whereas a 900 lumen CFL with a lifetime of 8500 hours needs to be replaced only three times. Lumen-hour is better functional unit than lifetime hour, because the main function of a lamp is to illuminate. Lumen-hour takes into account lamp technology by giving higher values to the technology with best efficiency in producing quality illumination. Lumen-hour is a functional unit that is well-suited for light source LCAs where the main function of the lamp is illumination for people. However, lumens and lumen-hours are not suitable functional units for horticultural lighting LCAs since plants require photons from a wider spectral range than what is visible for human eye.

Energy consumption (kWh) is measures the amount of kilowatts required to power a lamp for an hour. Energy consumption is the least popular functional unit in light source LCAs. An LCA for green products and materials used 1 kWh as a functional unit [29]. Energy consumption is easily derived from multiplying the power of the light source by lifetime hours. In the past, watts were used to quantify illumination for people. Now, lumens have replaced watts in illumination quantification for people. Therefore, energy consumption is not recommended as a functional unit to any light source LCA since it cannot reflect the function of a lamp sufficiently.

Photon-hour (molh) is a made-up metric that could measure the amount of photons a light source produces in an hour. Photon-hour in horticultural lighting LCAs would be the equivalent of lumen-hour in light source LCAs for people. Photon-hour is one of the two metrics that could serve as a functional unit in horticultural lighting LCAs.

Yield (kg or pcs) in horticulture is a measure used to express the fresh weight of crops. Yield is seldom expressed as dry weight or combined nutritional value of crops, although it is a possibility. Fresh weight of one ton of crops has been used as a functional unit LCAs studying crops, including wheat, oilseed rape, potatoes, and tomatoes [30]. Crops that are not measured in weight, such as flowers, use a different functional unit, for example, one hundred cut stems [31]. Fresh weight is a functional unit, which is easy to comprehend, and use for comparing other LCAs with similar crops. In addition, yield does take into account PPFD and spectra along with other factors, which affect crop growth. Therefore, this thesis recommends fresh weight to be used as the functional unit in future LCAs in horticultural lighting. Since the LCA experiment of this thesis focusses on cucumber seedlings and one ton of fresh weight is a widely used functional unit in agricultural and horticultural LCAs, the functional unit for this thesis will be the fresh weight of one ton of cucumber seedlings.

3.2 Life cycle inventory analysis

LCI is the second phase in the LCA methodology. The purpose of LCI is to collect data and perform calculations and analysis. LCI requires collecting the data of material and energy flows including the destination of these inputs and outputs.

3.2.1 Flow model

The flows of a unit process come in many forms of input and output as can be seen in Figure 3.4. Unit processes are connected to each other through flows.

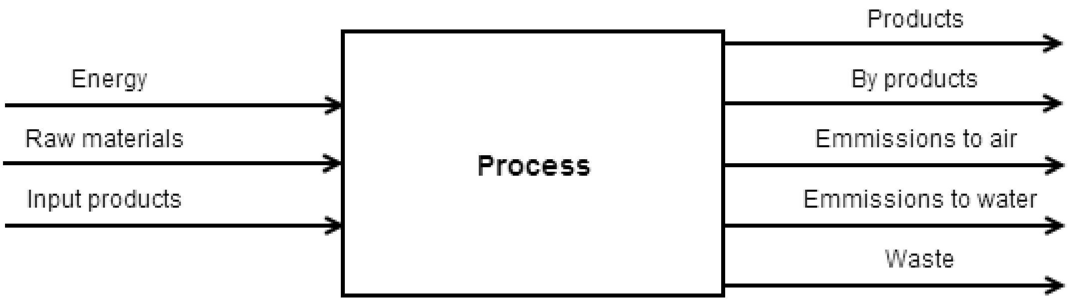

Figure 3.4. Input and output flows connected to a unit process.

The LCI flow model represents a material and energy balance over a product system. The flow model contains all the relevant inputs and outputs of a product system (see Figure 3.5). The model consists of unit processes, elementary flows in and out of the system, and flows inside the system. The flows are related to a reference flow, which are related to the functional unit. For example, raw aluminum input in luminaire manufacturing unit process is related to unassembled luminaire output, which is the reference flow of the unit process. All flows such as the reference flow unassembled luminaires, raw aluminum input, and elementary flows can be related to functional units by determining how many units (kg, tkm, MJ) of that flow is needed to produce one functional unit.

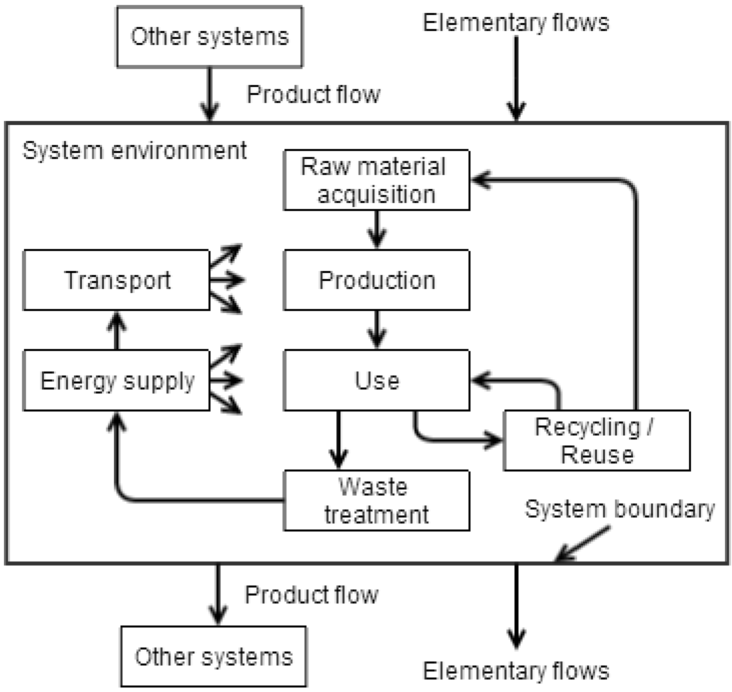

Figure 3.5. Example of a product system for LCA. Adapted from [15].

3.2.2 Life cycle inventory procedures

LCI is a collection of procedures defined in the standard ISO 14044 (see Figure 3.6). LCI is a procedure in itself, which is meant to define the input mass and energy amount as well as the output waste and emissions necessary in production of a product. The LCI procedures collect all the data, which is needed to perform the calculations and perform the final analysis. The procedures are as precise and accurate as is the data that is collected for the study. LCI is an iterative process, so during the processes it may be necessary to return to previous procedures to modify the data and continue the LCI from there.

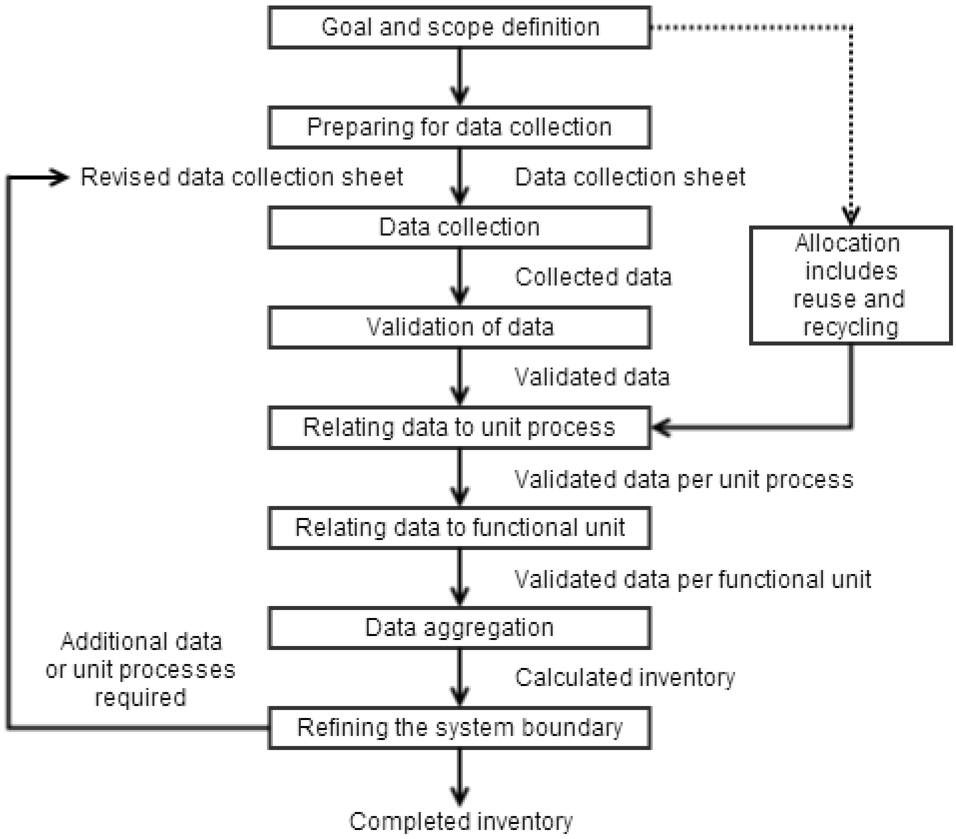

Figure 3.6. Simplified procedures for inventory analysis. Adapted from [16].

Preparation for data collection is a procedure where the methods of data collection and data quality requirements are considered. Preparation for data collection also includes the drafting of possible data collection sheets to manufacturers.

In *data collection* procedure, data is collected from various sources. This is usually the most time consuming part of LCA. Possible sources of data are presented in Table 3.2. The practitioner can utilize various methods in order to acquire data. The most common method of acquiring data by experimenting is to weigh the components and identify the manufacturing material in them. The manufacturer of the product can sometimes provide a bill of material for the studied product. A bill of material contains a complete list of parts used to manufacture the product. It is not common to obtain such a document, but the quality of the data in a bill of material is excellent. In addition, manufacturers sometimes publish environmental reports and even cradle-to-gate inventory analyses that can provide valuable data to the study. However, manufacturers are not the only source of data. Stakeholders such as consumers and municipal waste treatment facilities can provide useful data to some unit processes. Furthermore, conventional means to search information such as the Internet and libraries can provide decent data. There is also software that contains databases used to conduct LCA studies. LCA software databases contain detailed information of most of the materials and resources used in various components. If data cannot be acquired by any other way than estimation, then it should be used as a last method to acquire data.

Table 3.2. A table of possible sources of data.

Practitioner	Manufacturer	Stakeholders	External
Experimenting	Bill of material	Use data	Library
	Environmental reports	Disposal data	Internet
	Published LCI data		LCA databases
			Other LCA studies

Validation of data is a procedure where the collected data is validated by various methods such as checking the mass and energy balances or comparing data with other data sources. Validation also checks if the data quality requirements defined earlier have been met. Validation is an especially important procedure when the technology, time or location used in the study has a large impact on the results. However, validation can only be performed if the collected data is documented thoroughly enough.

The *validated data is related to unit processes*. In this procedure, an LCI flow model must finally be constructed if it has not been constructed before. All the flows can then be placed on the flow model and related to the reference flow. A spreadsheet is an excellent tool for this procedure. A flow can be related to a reference flow by dividing the quantity of the flow by the reference flow. This is the first calculation in an LCI and it is sometimes referred to as normalization.

In the next procedure, *data is related to functional unit* by establishing equations representing how the flows are related to the functional unit. The equations can be done to all flows. Usually, the equation is simple, for example, multiplying raw material output (that is already related to the reference flow) by a factor.

Data aggregation is a procedure where all the inputs and outputs are aggregated by summing the same resources and emissions together. Data can be aggregated thoroughly or not aggregated at all. A high level of aggregation makes a table easier to grasp at first glance, but it might hide some valuable information. A low level of aggregation may leave the LCI too detailed to grasp the big picture and information may as well be lost in this way.

The LCI results are then ready for the LCIA phase unless a sensitivity analysis needs to be performed. A sensitivity analysis might lead to an iterative process in the LCI where the system boundaries are refined and new data has to be collected or old data omitted. After all these steps and documentation, the LCI is finished.

3.3 Life cycle impact assessment

LCIA is a tool, which assesses the damage to humans, resources, and the environment caused by the product under study. The purpose of the LCIA is to improve the readability and comprehensibility of the study by presenting environmental impact in an understandable fashion. In other words, LCIA is translating the data collected in LCI phase to a more understandable format (e.g., SO_2 emissions are related to acidification). The results from LCI are material and energy flows whereas LCIA results are presented as environmental impacts. Therefore, LCI results cannot convey information about the proportion of the impacts or their causes to environment in the way LCIA results do. Thus, the LCIA phase is mandatory for an LCA study. If LCIA phase is not performed, the study is only an LCI study.

3.3.1 Risk assessment

LCIA is notably different from other types of impact analysis such as risk assessment. LCIA collects data from a wide range, unlike risk assessment, which concentrates on a few substances and their impacts. Risk assessment is a thorough analysis, well suited for risk prediction, whereas LCIA is better in linking a system and the potential impacts together and thus making the study more understandable. [32]

3.3.2 Life cycle impact elements

The ISO 14040 standard defines that an LCIA phase comprise of three mandatory and three optional elements that can be seen in Figure 3.7.

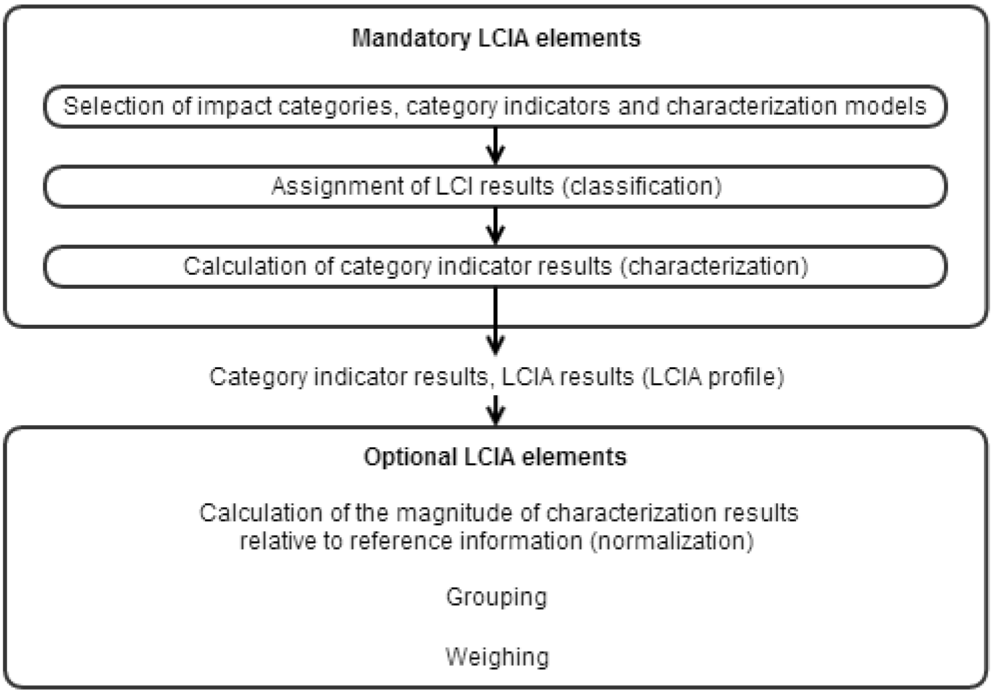

Figure 3.7. Elements of the LCIA phase. Adapted from [15].

Selection of impact categories, category indicators and characterization models is the first element of the LCIA phase. Impact categories are environmental threats to which impact category indicators such as waste and emissions are counted towards. Figure 3.8 further illustrates the meaning of impact categories and category indicators. A characterization model is used as a guideline on how to perform characterization. It is recommended to use existing impact categories, category indicators and characterization models so that the results are comparable with other studies. LCIA methodologies such as ReCiPe, which is going to be used in this thesis, help the practitioner to select the data needed to present results comprehensively.

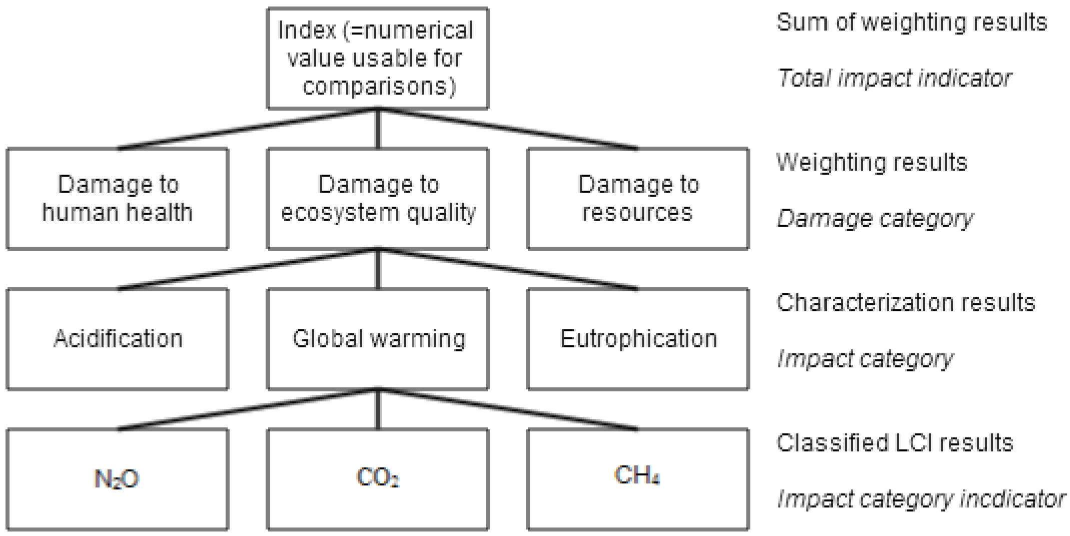

Figure 3.8. An example of the different terms used in LCIA as a tree presentation.

Sorting of LCI result parameters to impact categories is referred to as *classification*. The LCI results are assigned to one or multiple impact categories. Automatic classification is a standard feature in any LCIA methodology.

Characterization is the practice of calculating the magnitude of an environmental impact. Characterization uses characterization factors to convert LCI results into impact category indicators, which are directly comparable with each other. In other words, characterization enables the comparison of different impact category indicators within an impact category, for example, in the impact category “global warming”, a kilogram of methane has a “global warming potential” characterization factor of 21, because it is equivalent to 21 kg of CO_2.

Normalization is a calculation step, in which impact categories are related to (i.e., divided by) a reference value. This value can be based on various factors such as total regional emissions, total emissions per capita, or energy consumption of a household in a year. The purpose of normalization is to put the environmental impacts into perspective.

Grouping is a method used for sorting the impact categories into one or more groups. These groups can be sorted by characteristics (e.g., emissions, region) or a ranking system such as low/medium/high priority, which is based on value choices.

Weighing represents the importance of impact categories in relation with each other. Weighing is performed by first identifying the values from stakeholders. Based on these values, the weight of each impact category is determined. Lastly, these weights are applied to impact categories. Weighing is always based on subjective decisions, which are the first target for criticism in a study. LCIA methodologies offer many ready-made weighing options for the practitioner to choose from.

There are dozens of LCIA methodologies with own procedures of how to perform the mandatory and optional LCIA steps. Some LCIA methodologies have a final step, which is for *calculating the total impact indicator* (i.e., single score, single scale index). The total impact indicator is the sum of all impact categories.

3.4 Interpretation

Interpretation is a systematic technique to analyze and present the LCI and LCIA results. It is the fourth and final phase in LCA. Interpretation consists of three elements, which can be seen in Figure 3.9. Interpreting the results can be performed using various analyses, assumptions, and values choices of the practitioner. Therefore, interpretation is not a straightforward method to assess if product A is better than product B. However, interpretation is always a valuable tool in comparing products, because even if the interpretation gives uncertain results, it still helps the decision makers to gain a better understanding of the products.

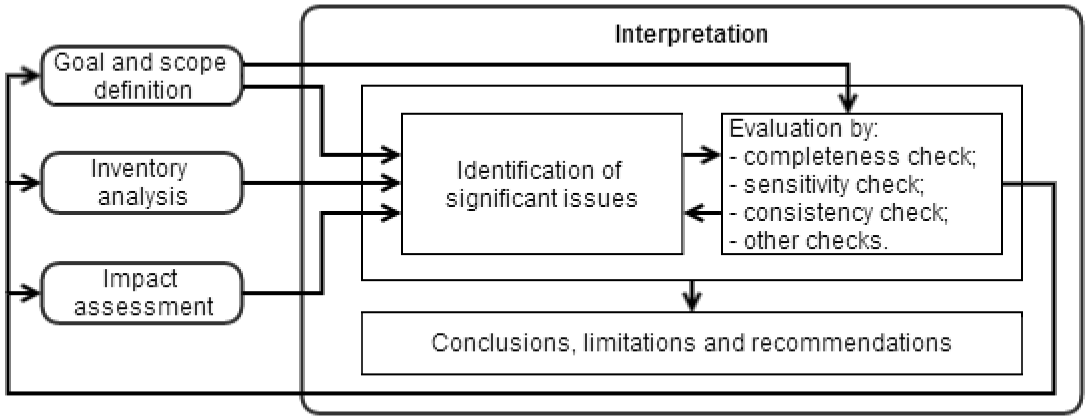

Figure 3.9. Relationships between elements within the interpretation phase with other phases of LCA. Adapted from [16].

3.4.1 Identification of significant issues

Identification of significant issues is the first element of the interpretation phase. Interpretation consists of one or multiple analyses that focus on finding significant issues regarding different aspects of the study. These analyses include dominance, contribution, break-even, and decision maker analysis.

Dominance analysis is used to find which process has the greatest (dominant) environmental impact. A chart can be drawn, where the horizontal axis lists processes as single unit processes or grouped unit processes (e.g., use, transport). The vertical axis is a value depicting the magnitude of different processes.

Contribution analysis is similar to dominance analysis, except that it focuses on environmental loads instead of processes. In the contribution analysis chart, the horizontal axis lists impact category indicators and the vertical axis is a reference value like in the dominance analysis.

Break-even analysis reveals which products are least harmful to the environment given a number of uses. This analysis is useful in products that are recyclable or have many alternatives, which all perform the same task.

Decision maker analysis is used to identify the stakeholders involved in different stages of the system process. This is relevant when there are many stakeholders involved in a products life cycle.

3.4.2 Evaluation

The second element of the interpretation phase is the evaluation of the completeness, sensitivity, and consistency of the data. The robustness of the study will be evaluated by using a series of checks including completeness, sensitivity, and consistency.

Completeness check is used to find the data gaps in LCI or LCIA. The completeness of the data is assessed by revising the data with a checklist based on the goal and scope. Completeness check is usually supplemented by a sensitivity check.

The purpose of a *sensitivity check* is to evaluate the reliability of the results identified as significant issues (i.e., first element of interpretation). A sensitivity check comprises of a contribution, uncertainty, and sensitivity analysis.

1. Contribution analysis is similar in evaluation element as in identification of significant issues.
2. Uncertainty analysis is used to deal with unreliable data. In this analysis, products or processes can be compared by presenting the range of environmental impact with, for example, a 95 % probability to be accurate.
3. Sensitivity analysis is also a way to deal with unreliable data. Sensitivity analysis changes the input parameters systematically in a product inventory, resulting in an outcome revealing the probability of a product causing less environmental impacts than its alternative.

The final check, *consistency check*, is used to evaluate if the modeling and methodological choices have been consistent in the study. The consistency check may be based on a checklist consisting of various categories such as data source, technological representation, and system boundaries.

Additional checks can include more robustness tests such as variation analysis and data quality assessment. *Variation analysis* is used to investigate what happens to the LCA if a product system is altered by changing, for example, its energy source. *Data quality assessment* focuses on identifying the degree of data gaps, approximate data and appropriate data.

3.4.3 Conclusion

The interpretation phase is concluded in the last element, where the practitioner states conclusions, limitations, and recommendations. This step follows the principles of a standard scientific conclusions part. The conclusion focuses mainly on interpreting the analyses and checks made in the interpretation phase. Now, the practitioner can answer the questions asked in the goal and scope phase such as which process is the biggest cause for global warming. Conclusions are presented along with limitations that state what data could not be normalized, weighed, processed, or included in the study. The conclusions will be used as a basis to give recommendations to stakeholders. Recommendations are often focused on improving processes and choosing the option with lowest environmental impacts.

4 Life cycle assessment experiment

The goal of this chapter is to provide an example of how to conduct a comparative LCA for artificial light sources used in horticultural lighting. The experiment is conducted in a fashion that is easy to follow even for readers with no previous experience with LCA. This experiment is meant to promote discussion about uniform methods in future LCA studies related to horticultural lighting. Thus, the documentation of each step in this experiment is more important than the actual results. The focus of this report is to strive for easy readability and promote transparency.

The two luminaires studied in this comparative LCA are interpretations of the HPS luminaire and the LED luminaire #8 used in the growth experiment in Piikkiö, Finland. These luminaire interpretations attempt to be as accurate as possible without the help of a complete bill of material. The LED luminaire is based on the LED luminaire seen in Figure 4.1. The HPS luminaire is based on three generic components: 250 Watt lamp, ballast, and aluminum lamp holder.

Figure 4.1. An LED luminaire and a generic HPS luminaire.

A computer aided greenhouse simulation for horticultural lighting is optional. Greenhouse simulations improve the accuracy of an experiment. However, an actual growth experiment is always more accurate than a computer simulation, which is vulnerable to assumptions and missing data. Moreover, a greenhouse simulation that is based on suggested illumination (i.e., luxes) on a surface is not possible while studying horticultural lighting effects on plants. Luxes are based on lumens, which are used to measure the total amount of visible light emitted, but plants require photons from a wider wavelength area than what human eye can see. Moreover, it is not possible to convert lumens into radiative power unless the spectral composition of luminaire is known. In addition, the composition of a luminaires spectrum affects plant photomorphogenesis and yield even though the radiative power is similar between different luminaires. Therefore, different luminaires are not comparable in a computer simulation due to a unique spectrum in each luminaire.

A simulation able to tell the amount of luminaires required to produce a set amount of crops in set amount of time would be useful, if there was a way to do such a simulation. For the purpose of this thesis, a small growth experiment will be enough to deduce results. Based on the Piikkiö growth experiment this thesis assumes that the HPS luminaire is over 40 % more efficient than the LED luminaire in producing cucumber seedlings over a period of 21 days in similar conditions.

The structure of this experiment follows the framework that was presented in the previous chapter. First the goal and scope are defined, followed by an LCI construction, LCIA, and conclusions.

4.1 Goal and scope

LCA studies start with the goal and scope phase. For a methodology review of goal and scope please see section 3.1. This goal and scope phase follows the framework discussed in the methodology chapter.

4.1.1 Goal

The application of this study is to act as a guide for how to perform a comparative LCA. This experiment sets to find out which technology, LED or HPS, is environmentally friendlier in cucumber seedling production.

The reason for carrying an LCA study about horticultural lighting is because there have been several studies related to light sources and crop production, but not a comparative study that assesses the artificial light sources used in horticultural lighting. Thus, this LCA is unique and can contribute new information about artificial light sources used in horticultural lighting and the practice of LCA in horticulture.

The audience of this study is greenhouse owners, luminaire manufacturers, and people interested in learning how to perform a comparative LCA.

4.1.2 Product system of a horticultural luminaire

The product system of horticultural light source consists of several unit processes, which can be examined in Figure 4.2. This rough basic flow model applies for both HPS and LED luminaire.

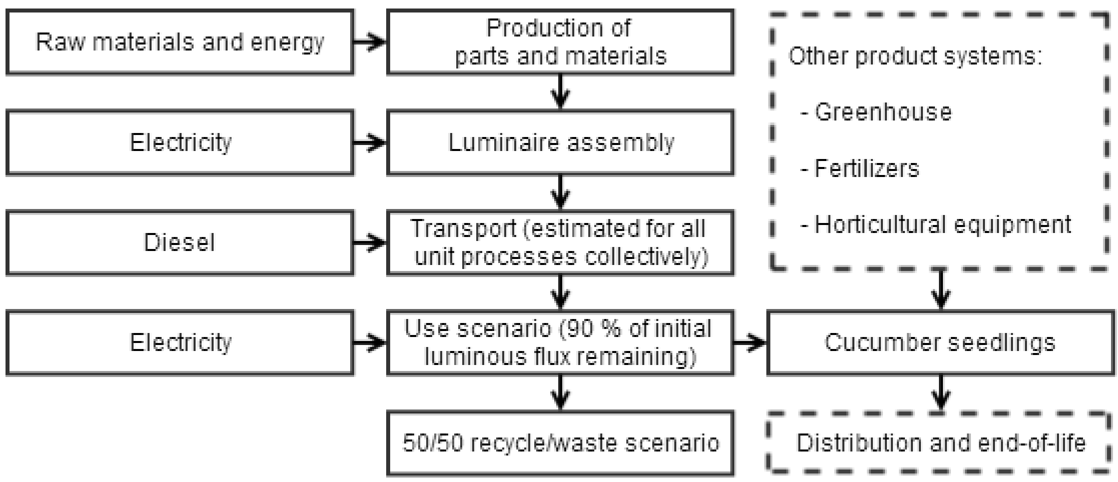

Figure 4.2. A basic flow model for a luminaire used in horticultural lighting including the end product and cut-off unit processes.

The unit process, production of parts and materials, includes the extraction of raw materials and production of luminaire parts such as heat sink, ballast, and die/lamp. This unit process actually consists of many unit processes, but for the sake of readability all unit procuresses are condensed into a single one. The manufacturing location for both luminaires is Shanghai, China.

Luminaire assembly includes packaging and the electricity required to put together the luminaire parts. Packaging is necessary for parts, materials, and the complete luminaire. Packaging as well as assembly has very small environmental impacts compared to other unit processes.

All transports are combined into one unit process. The transport scenario is as follows: the luminaires are shipped from China to Europe. Luminaires are then further distributed to vendors by trucks. Other transports such as trucks inside China, consumer transports, and disposal are very small. Therefore, transports can be included into a single truck transport activity.

The lifespan of a luminaire is determined to be at the end when the luminous flux is reduced to 70 % of the initial amount. In horticultural lighting this figure is 90 % [4].

The end-of-life in the life cycle of a luminaire is an assumed scenario where half is recycled and the other half is disposed to a land fill. A more realistic scenario would be that 1 out of 10 luminaires is recycled properly and the rest are disposed by other means.

4.1.3 System boundaries

This LCA is a cradle-to-grave study that has a focus on the artificial light sources used in horticultural lighting. Other product systems affecting the yield have been left out from this study. These product systems include for example, the greenhouse, fertilizers, and other horticultural equipment.

The s*tarting point of the product system* in this LCA is raw material extraction of minerals needed for luminaire parts. It is assumed that the equipment for raw material extraction already exists.

The g*eographical area* of this study is limited to Finland where the crops are grown. Therefore, the luminaires use Finnish electricity mix as their source of electricity. Luminaires are assumed to be manufactured in China and transported by freight to Europe and from ports to distribution hubs by trucks.

The t*ime-related boundary* for this LCA is set in the time period when the Piikkiö cucumber seedling growth experiment was started January 23rd, 2012 and terminated February 13th, 2012. The experiment lasted for 21 days.

The *technology boundary* restricts this LCA for only recent HPS and LED technology. Other artificial light sources, which are more uncommon in horticultural lighting such as ceramic metal halide lamp, compact fluorescent lamp, and sulfur lamp, are cut-off from the study.

Crop boundary limits the number of crops studied to only one. This crop is cucumber (Cucumis sativus) seedling.

4.1.4 Allocation

The allocation procedure for this experiment is a simple one. Firstly, the co-products of the product system are defined. The only co-product the simplified horticultural lighting product system produces is recycled luminaires. Secondly, the co-product is allocated back to the product system into the production unit process. The allocation is performed only while assessing environmental impacts by adding the positive effect of recycling to environmental impacts of luminaire production.

4.1.5 Data quality requirements

The data collection of this study aims to fulfill high quality standards in relevance, reliability, and accessibility. High quality data is however not mandatory as most of the data is collected from open sources, which can limit data quality.

Precise data for the luminaires can be obtained from the manufacturer in the form of bill of materials, which they are reluctant to give. When precise data is not available, the study has to rely on data from product datasheets, public databases and other LCAs, which can have a negative effect on the reliability of the study.

Transparency relates to credibility, which in turn relates to reliability of the study. Transparency in addition relates to reproducibility and that relates to accessibility. In order to fulfill the goal of using this experiment as a guide for how to perform a comparative LCA, transparency is definitely one of the most important data quality requirements of this thesis. This experiment will reveal all data sources it has used and the reasoning behind calculations.

4.1.6 Assumptions and limitations

The assumptions of this study are made to simplify the LCA process. Many details and factors that have a very small contribution are either omitted from the study or simplified as an assumption. The product system for instance assumes that the transports happen in only one unit process collectively. The recycle scenario is also an assumption, because it does not have a large effect on the outcome. Assumptions and limitations will be listed when it is relevant to the context.

4.1.7 Critical review

The critical review of this LCA study will be done by an informal internal peer review. The LCA will be reviewed after it is complete. The review will address scope, data acquisition methods, assumptions, results, and conclusions.

4.2 Life cycle inventory analysis

The LCI of both the HPS and the LED luminaire are studied in the second phase of this LCA. The LCI methodology will follow the procedures from international standards, which were discussed in chapter 3.2. The procedures are tracked using a spreadsheet for data collection and calculations.

4.2.1 Data collection

LCI data was collected mainly from manufacturer brochures, datasheets and credible LCAs. As expected, the manufacturers were reluctant to provide a bill of material or any other information that was not already available for the public. However, the Piikiö growth experiment data was acquired successfully through an e-mail inquiry (see Appendix A).

Basic data for the LED luminaire #8 used in the growth experiment was deduced from a product brochure for similar luminaires with only different dimensions. Likewise, the basic data for the HPS luminaire was acquired directly from a datasheet for the lamp. Intuitively, the weight and power consumption of the luminaire are both greater than the weight and power of lamps/dies. The basic information for ballasts was acquired from several ballast manufacturers product specifications. All the basic data can be seen in Table 4.1.

Table 4.1. Basic data for luminaires.

Characteristics	Units	LED	HPS
Number of die/lamps per luminaire		45	1
Ballast power efficiency		0,9	0,9
Ballast weight	kg	0,7	1,1
Power consumption per die/lamp	W	2,0	250
Power consumption per luminaire	W	101,9	277,8
Typical lamp lifetime (10% luminous decay)	h	35000	21000
Typical luminaire lifetime	h	35000	42000
Total electricity consumed through lifetime	kWh	3566,5	11666,7
Luminaire weight	kg	6,7	10,9

The electronic ballast components are assumed to be similar for both luminaires. The electronic ballast will be modeled after the electronic ballast used for an LED luminaire in another notable LCA study [10]. The weights of the electronic ballast components are adjusted to fit the power consumption of both luminaires. The LED luminaire with lower power consumption will contain electronic ballast weighing a total of 0.7 kg, whereas the HPS luminaire electronic ballast will weigh 1.1 kg. The power factor for both ballasts is 0.9.

The inventory data for the LED luminaire is based on an LED lamp LCI made by Navigant consultancy. Their LCI is the most accurate inventory possible, because it is based on a bill of material provided by the lamp manufacturer. The Navigant lamp LCI is modified to fit the purpose of this thesis and the basic specifications of the LED luminaire. The modifications consist of multipliers and assumptions. Table 4.2 shows the simplified material list for the LED luminaire. A complete inventory for the LED luminaire is listed in appendix B.

Table 4.2. Material list for the LED luminaire.

Part	Details	Amount	Part	Details	Amount
Ballast	Rigid foam	7,7 g	Fitting	Aluminum parts	5534,0 g
Ballast	Inductor	15,4 g	Fitting	Metal clips	84,4 g
Ballast	Inductor	10,3 g	Fitting	Wiring	28,1 g
Ballast	Zener diodes	0,3 g	Lamp	Pins	0,3 g
Ballast	Capacitors	12,9 g	Lamp	Base contacts	1,1 g
Ballast	Resistors	25,7 g	Lamp	Solder Paste	0,6 g
Ballast	Transistors	7,7 g	Lamp	2 Watt LED	84,4 g
Ballast	Aluminum block (PCB)	514,5 g	Lens	Glass tube	84,4 g
Ballast	Wiring	5,1 g	Lens	Coating	2,8 g
Ballast	Solder Paste	2,6 g	Packaging	Corrugated cardboard	200,0 g
Ballast	Housing	90,0 g			
Ballast	Integrated circuit	2,6 g			
Ballast	PET Film	5,1 g			

The weight of the LED luminaire is interpolated from the product brochure of two similar luminaires with only different dimensions. The following equation was used to interpolate the weight of LED luminaire and add 200 grams of assumed packaging:

$$m_{LED} = m_1 + (m_2 - m_1) * \frac{l_{LED} - l_1}{l_2 - l_1} + \mathrm{m}_p \qquad (3)$$

where

$m_{LED,1,2,p}$ is the mass of LED luminaire #8, brochure luminaires, and packaging
$l_{LED,1,2}$ is the length of LED luminaire #8, and brochure luminaires.

Table 4.3. Material list for the HPS luminaire.

Part	Details	Amount	Part	Details	Amount
Ballast	Rigid foam	12,1 g	Fitting	Ceramic bulb holder	176,9 g
Ballast	Inductor	24,3 g	Fitting	Weather guard	10,2 g
Ballast	Inductor	16,2 g	Fitting	Black plastic insulator	73,9 g
Ballast	Zener diodes	0,4 g	Fitting	Photocell cap	24,4 g
Ballast	Capacitors	20,2 g	Fitting	Photocell plastic	11,3 g
Ballast	Resistors	40,4 g	Fitting	Photocell plugin	45,3 g
Ballast	Transistors	12,1 g	Fitting	Wiring	60,0 g
Ballast	Aluminum block (PCB)	808,5 g	Fitting	Aluminum parts	8792,4 g
Ballast	Wiring	8,1 g	Lamp	Circuit board	40,8 g
Ballast	Solder Paste	4,0 g	Lamp	Circuit board copper	5,1 g
Ballast	Housing	141,5 g	Lamp	Felt heat shied	2,9 g
Ballast	Integrated circuit	4,0 g	Lamp	Paper insulator	1,3 g
Ballast	PET Film	8,1 g	Lamp	Plastic circuit board	22,8 g
Lens	Light bulb	114,4 g	Lamp	Big capacitor	220,9 g
Packaging	Corrugated cardboad	300,0 g	Lamp	Circuit board capacitor	7,1 g
			Lamp	Diode	0,4 g

The inventory data for the HPS luminaire is based on a street lighting study, which opened an HPS luminaire for inspections [24]. The researchers weighed and identified the content found inside. This is a recent study and regarded as a high quality LCA among industry experts [28]. Division of the material list into luminaire parts has been left untouched in respect of the street lighting study. Table 4.3 contains the simplified inventory and Appendix B the complete inventory for the HPS luminaire.

The weight of the HPS luminaire is based on a generic 250 Watt HPS luminaire. In eBay, the search words "250 Watt HPS luminaire" return seven relevant results. From these seven results two lightest and two heaviest are omitted. The mean weight of the remaining three luminaires is 10.86 kg including packaging.

Most of the original inventory data is multiplied by the relation of the dies/lamps in a luminaire. The multiplier for lamp parts in the HPS luminaire is 1. In the LED luminaire, the lamp from the original inventory has 16 dies and in this experiment it has 45 dies. The lamp multiplier is derived from dividing the number of dies in the experiment luminaire by the dies in the original inventory.

The ballast multipliers come from dividing the total weight of the ballast by the total weight of the original inventory data ballast components. The following equation can be used for both the smaller and the bigger ballast:

$$x_b = \frac{m_b}{\sum_{i=1}^{n} m_i} \tag{4}$$

where

x_b is the ballast multiplier
m_b is the mass of the ballast
m_i is the weight of a ballast component.

The weight of packaging, lamp holder and other aluminum parts are assumptions. These weights are assumptions, because they do not scale similarly as the rest of the inventory. The weight and size of the aluminum parts increases exponentially as luminaire power consumption increases. Therefore, the largest portion of the total luminaire weight comes from aluminum parts.

4.2.2 Validation of data

Both of the original inventories are already validated by the studies they were taken from. Mass balance is checked to ensure that the weight of the components is equal to the total weight of a luminaire. The data quality requirements have been met so far by explaining the inventory data source, multipliers and assumptions.

4.2.3 Data relation

The flows of all unit processes can be placed on a spreadsheet, in order to relate data to unit processes and functional unit. The spreadsheet follows the LCI flow model for horticultural light sources, which is already defined before in Figure 4.2. Table 4.4 representing this spreadsheet holds all the essential LED inventory data. A similar spreadsheet for the HPS luminaire is presented in Table 4.5. Emissions and waste have been omitted from the tables due to the staggering number of compounds that would have to be listed in outflows. However, emissions and waste will be examined in the LCIA phase.

Table 4.4. LCI spreadsheet for the LED luminaire.

Production	Unit	Data as collected for 1 luminaire during its lifetime	Normalization to reference flow (1 kg luminaire)	Normalization to functional unit (1000 kg plants)
Inflows				
Polyurethane	kg	0,007717751	0,001148475	0,017565293
Cast iron	kg	0,015435502	0,00229695	0,035130587
Copper	kg	0,044966752	0,006691481	0,102342536
Diode	kg	0,000257258	3,82825E-05	0,00058551
Aluminum	kg	6,14853589	0,914960698	13,99382279
Resistor	kg	0,025725836	0,003828249	0,058550978
Transistor	kg	0,007717751	0,001148475	0,017565293
Solder paste	kg	0,003135084	0,00046653	0,007135325
Polypropylene	kg	0,090040426	0,013398873	0,204928424
Integrated circuit	kg	0,002572584	0,000382825	0,005855098
Polyethylene	kg	0,005145167	0,00076565	0,011710196
1 Watt LED	kg	0,084375	0,012555804	0,192034139
Glass	kg	0,084375	0,012555804	0,192034139
Cardboard	kg	0,2	0,029761905	0,455192034
Outflows				
Unassembled luminaire	kg	6,72	1	
Assembly				
Inflows				
Unassembled luminaire	kg	6,72	1	
Manufacturing	kg	0,08634375	0,012848772	0,196514936
Outflows				
Luminaire	kg	6,72	1	
Transport				
Inflows				
Luminaire	kg	6,72	1	
Transoceanic freight ship	tkm	9,82	1,461309524	22,34992888
Truck, 200 km	tkm	0,1	0,014880952	0,227596017
Outflows				
Luminaire	kg	6,72	1	
Use				
Inflows				
Luminaire	kg	6,72	1	
Use, electricity	kWh	3566,5	530,7291667	8117,211949
Outflows				
Luminaire	kg	6,72	1	**15,29445235**
Cucumber seedling	kg	439,375	65,38318452	**1000**
End-of-life				
Inflows				
Luminaire	kg	6,72	1	

Outflows				
Recycling, electronic scrap	kg	3,26	0,485119048	7,419630156
Recycling, cardboard	kg	0,1	0,014880952	0,227596017
Disposal, electronic scrap	kg	3,26	0,485119048	7,419630156
Disposal, cardboard	kg	0,1	0,014880952	0,227596017

The first column states the unit process where an activity or a component belongs to. The activities and components are divided into inflows and outflows. The components and activities are resources that can be found on life cycle databases such as Ecoinvent. However, some activities are not yet found in life cycle databases. For example, the inventory models the 2 W die as a 1 W die, because there is no 2 W die in Ecoinvent. The same applies for the assembly activity as it is modeled after the activity "electric component manufacturing". It is also assumed that the manufacturing weight consists of lamp components only.

The second column is for units. There are three units: kilogram (kg), metric ton kilometer (tkm), and kilowatt-hour (kWh). Kilogram is the basic unit for measuring weight. Metric ton kilometer is a widely used unit in transportation. It takes into account the weight and the dimensions of the good transported. Kilowatt-hour expresses energy consumption.

The third column holds the data that was acquired during data acquisitions. It holds the multipliers and assumptions discussed before. The numbers are a sum of many components, for example, aluminum consists of capacitors, coating, metal clips, and other aluminum parts. The equation used to count cucumber seedlings a luminaire produces during its lifetime is as follows:

$$m_{ct} = n * m_{cg} * \frac{t_{lum}}{t_g} \qquad (3)$$

where

m_{ct} is the yield a luminaire produces during its lifetime
n is the highest potential number of plants that fit to grow under a luminaire during a cycle while holding similar conditions for every plant
m_{cg} is the fresh weight of a cucumber seedling in the Piikkiö experiment
$\frac{t_{lum}}{t_g}$ is a multiplier where luminaire lifetime is normalized to growth cycles.

The variable n can only be determined in a growth experiment or a computer simulation. Since the Piikkiö growth experiment does not provide this number, it is assumed that both luminaires can grow 100 cucumber seedlings simultaneously in a 21 day cycle while holding similar conditions for every plant.

The fourth column is where the data from third column is normalized to outflows of a unit process. In this inventory the outflow is an unassembled, assembled, or disposable luminaire. Therefore, the data in fourth column is simply the data from third column divided by 6.72.

The fifth column relates the data from data normalized to 1 kg of luminaire into the functional unit 1000 kg of cucumber seedlings. The cucumber seedling cell that is bolded in the table is set to 1000. The bolded cell above cucumber seedling depicts how many kg of luminaire is needed to produce 1000 kg of cucumber seedlings. It comes from dividing the functional unit (1000 kg) by the amount of cucumber seedlings produced with 1 kg of luminaire (65,38 kg). This factor (15,29) is used to derive the data in fifth column by multiplying the data in the fourth column by it.

Table 4.5. LCI spreadsheet for the HPS luminaire.

Production	Unit	Data as collected for 1 luminaire during its lifetime	Normalization to Reference flow (1 kg luminaire)	Normalization to functional unit (1000 kg plants)
Inflows				
Polyurethane	kg	0,012127894	0,001061462	0,016413074
Cast iron	kg	0,024255788	0,002122924	0,032826149
Copper	kg	0,094442988	0,008265875	0,127812773
Diode	kg	0,001259263	0,000110214	0,001704202
Aluminum	kg	10,07720643	0,88198105	13,6378118
Resistor	kg	0,040426314	0,003538207	0,054710248
Transistor	kg	0,012127894	0,001061462	0,016413074
Solder paste	kg	0,004042631	0,000353821	0,005471025
Polypropylene	kg	0,352077898	0,030814694	0,476478491
Integrated circuit	kg	0,085642631	0,007495647	0,115902963
Polyethylene	kg	0,008085263	0,000707641	0,01094205
Ceramic	kg	0,1769	0,015482708	0,239404534
Felt	kg	0,005734	0,000501853	0,007760009
Paperboard	kg	0,0025206	0,000220609	0,00341121
Glass	kg	0,2288	0,02002512	0,309642495
Cardboard	kg	0,3	0,026256713	0,405999774
Outflows				
Unassembled luminaire	kg	11,4256496	1	
Assembly				
Inflows				
Unassembled luminaire	kg	11,4256496	1	
Manufacturing	kg	0,06024992	0,005273216	0,08153818
Outflows				
Luminaire	kg	11,4256496	1	
Transport				
Inflows				
Luminaire	kg	11,4256496	1	
Transoceanic freight ship	tkm	16,69641058	1,461309524	22,59579643
Truck, 200 km	tkm	0,170024548	0,014880952	0,23009976
Outflows				
Luminaire	kg	11,4256496	1	
Use				
Inflows				
Luminaire	kg	11,4256496	1	
Use, electricity	kWh	11666,66667	1021,094386	15788,88012
Outflows				

Luminaire	kg	11,4256496	1	**15,46270387**
Cucumber seedling	kg	738,9166667	64,67174231	**1000**
End-of-life				
Inflows				
Luminaire	kg	11,4256496	1	
Outflows				
Recycling, electronic scrap	kg	5,5628248	0,486871644	7,528352047
Recycling, cardboard	kg	0,15	0,013128356	0,202999887
Disposal, electronic scrap	kg	5,5628248	0,486871644	7,528352047
Disposal, cardboard	kg	0,15	0,013128356	0,202999887

The spreadsheet for HPS luminaire has similar columns and formulas as the spreadsheet for LED luminaire, but the HPS inventory has additional assumptions. Even though the weight of the luminaire is 10.86 kg, the inventory includes a replacement lamp, because the lifetime of the luminaire is 42000 h and the lifetime of an HPS lamp is 21000 h. The assembly of the luminaire is modeled with electronic component manufacturing as the LED lamp. This activity is divided by a factor of 10 due to a lower energy demand in order to produce an HPS lamp compared to LED lamp.

The inventory is now ready for the LCIA phase. Data aggregation has already been made for inputs such as aluminum. Outputs have not been aggregated since they have been left out from the table. The inventory results are considered to fulfill the data requirements of this experiment and no further sensitivity analysis is necessary. Therefore, the system boundaries do not need to be refined. Thus, the LCI is now complete.

4.3 Life cycle impact analysis

The next phase in the LCA experiment is the LCIA. To help the LCIA process, this thesis uses a ready-made LCIA methodology. There are several different ready-made LCIA methodologies available. Some methodologies are better suited to certain LCAs than others. This experiment will be using the default ReCiPe endpoint method “ReCiPe Endpoint (H,A)” as its LCIA methodology due to its popularity among LCA practitioners. The H,A stands for the Hierarchist version of ReCiPe, with the European normalization and average weighing set. Hierarchist version is an environmental scenario that portrays the future in a conservative way, where no significant changes are made in global environmental policy or objectives.

4.3.1 Impact categories, category indicators and characterization models

LCIA databases and ready-made methodologies are a great help in choosing impact categories, category indicators and characterization models. Ecoinvent is both an LCI and an LCIA database. It contains information from the results of numerous LCAs, product and activity data, are other studies and research within the database. There are a vast amount of different category indicators listed in the Ecoinvent database. All these category indicators are already linked to impact categories depending on the characterization model. The ReCiPe Endpoint (H,A) LCIA methodology has already predefined the characterization model and thus all the category indicators linking to impact categories.

The Ecoinvent database lists several impact categories for the ReCiPe Endpoint (H,A) LCIA methodology. This thesis will focus on the three damage categories, which already consist of all the important impact categories. The damage and impact categories are listed in Table 4.6.

Table 4.6. Impacts categories in the ReCiPe LCIA methodology.

ReCiPe Endpoint (H,A)		
Ecosystem quality	**Human health**	**Resources**
Climate change, ecosystems	Climate change, human health	Metal depletion
Urban land occupation	Human toxicity	Fossil depletion
Freshwater eutrophication	Photochemical oxidant formation	
Agricultural land occupation	Ozone depletion	
Freshwater ecotoxicity	Particulate matter formation	
Terrestrial ecotoxicity	Ionising radiation	
Marine ecotoxicity		
Natural land transformation		
Terrestrial acidification		

4.3.2 Classification and characterization

After defining the impact and damage categories, the LCI results are compiled into a spreadsheet. The LCI results are simply the names of different activities and their weight normalized per functional unit, which was the last column in Table 4.4 and Table 4.5. The names of the flows are then used as a reference to find a suitable name from the Ecoinvent LCIA database. The database is a huge workbook consisting of tens of sheets sorted by activities in rows and different LCIA methodologies in columns. A suitable LCIA name can be found by typing the LCI name into a search box and find all instances in the workbook. For example searching for “copper” gives several search results from which “copper//[GLO] market for copper” is the most suitable for this LCA. The components are manufactured in China, but since the database lacks information, the region is modeled as global (GLO). Finnish electricity mix is used for electricity, because cucumber seedlings are assumed to be grown in Finland. The mode of production for electricity in Finland is presented in Figure 4.3.

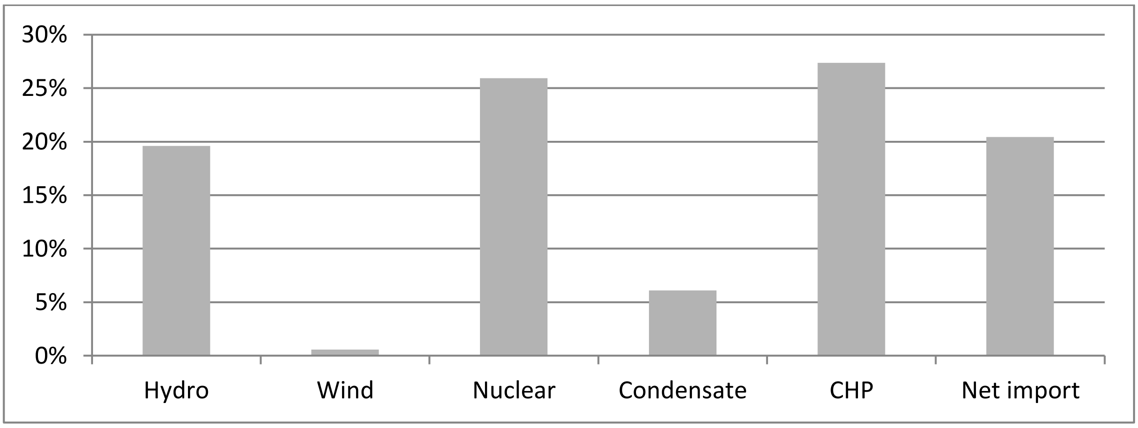

Figure 4.3. Electricity by mode of production in Finland in 2012 [33].

The values of ReCiPe damage categories of each activity are then copied from the database into a spreadsheet in order to calculate the magnitude of environmental impacts. The magnitude is calculated by multiplying the weight normalized per functional unit by a weighing factor and by the ReCiPe damage category value for 1 unit of activity. The manual weighing factor is 1 for all activities, except for the 1 Watt LED. Figure 4.4 shows the environmental impacts grouped into damage categories for the LED and the HPS luminaire.

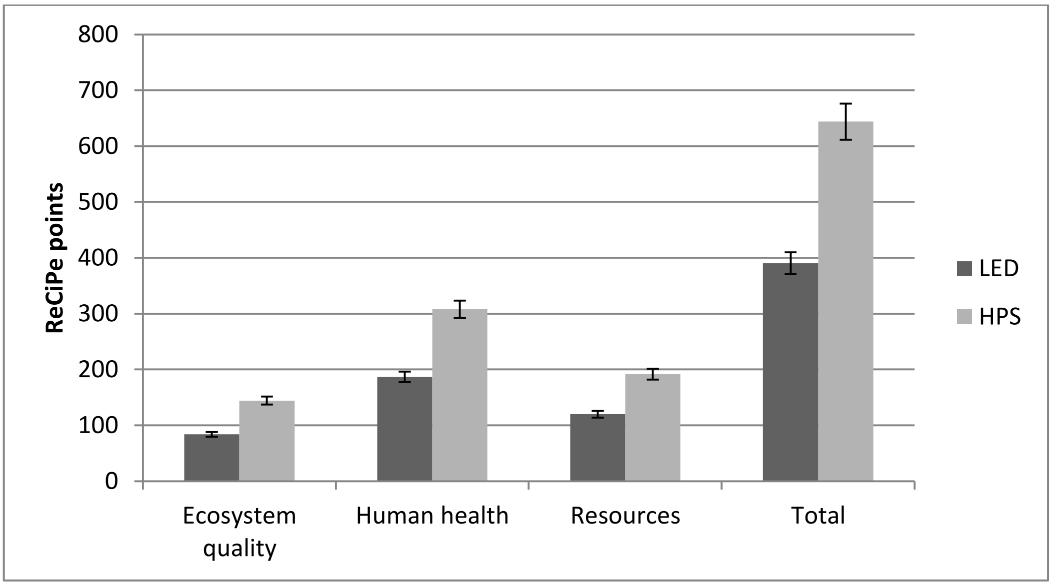

Figure 4.4. Environmental impacts grouped into damage categories for the LED and HPS luminaires using one ton of cucumber seedlings as functional unit.

4.3.3 Optional LCIA elements

Most of the activities have already been weighed by the ReCiPe methodology. However, the weight of the LED die is further multiplied by a factor of 5 due to estimation that the environmental impacts of the diode in the database are underestimated [34].

Grouping is performed in order to condense information and improve readability. The impact categories have already been grouped into damage categories before.

Normalization helps to explain the meaning of ReCiPe points. The normalization reference will be the energy consumption of a generic Finnish apartment per year. The total energy consumption of all Finnish apartments was 61 884 GWh in 2011 [35]. The total number of Finnish apartments was 2866000 in 2012 [36]. The energy consumption of a generic Finnish apartment can be derived by dividing the energy consumption by the number of apartments. The result (21592 kWh/a) is then multiplied by the total value of every damage category in ReCiPe for Finnish low voltage electricity mix. The result shows that an average apartment consumes 798 ReCiPe points worth of electricity per year. This value can be used to compare the environmental impacts of one functional unit. For example, producing 1000 kg of cucumber seedlings with HPS luminaires is 19 % less taxing for environment than the electricity usage of an average Finnish household per year. With LED luminaires this number is 51 %.

4.4 Interpretation

The identification of significant issues in this experiment consists of dominance analysis and contribution analysis. Evaluation includes a completeness check, sensitivity check, consistency check, and a variation analysis.

4.4.1 Dominance analysis and contribution analysis

The dominant activity causing greatest environmental impacts is identified with a dominance analysis. It compares the environmental impacts of activities. Figure 4.5 presents a dominance analysis for the LED and HPS luminaires.

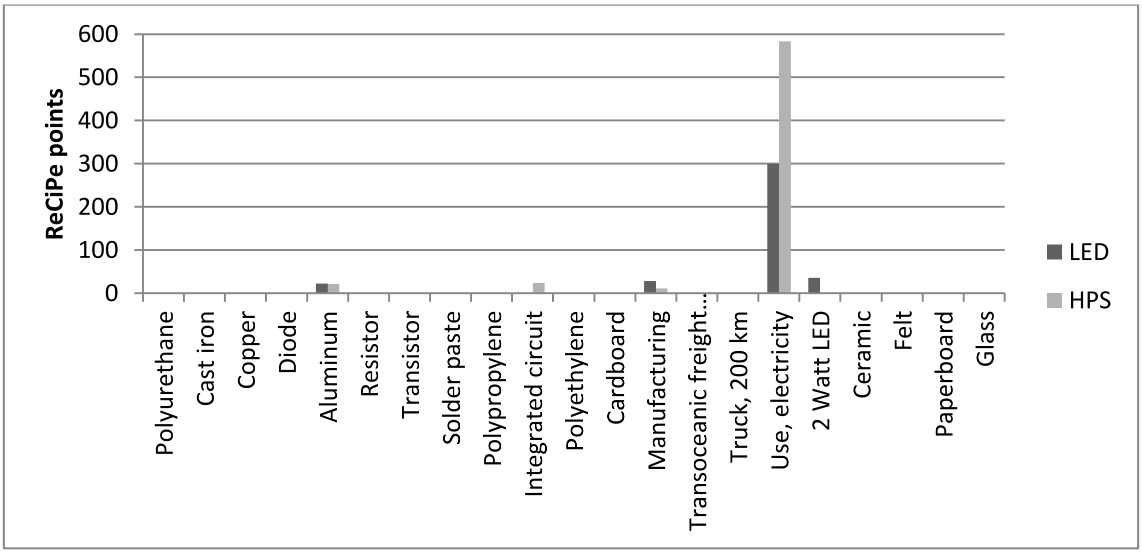

Figure 4.5. Electricity use is the dominant activity in horticultural lighting. Chart is using one ton of cucumber seedlings as functional unit.

Contribution analysis resembles dominance analysis, but the axis with activities is replaced by environmental impacts. Due to a large number of environmental impacts, this contribution analysis focuses only on human health, which is the greatest damage category for both luminaires. Figure 4.6 shows the details for the contribution analysis.

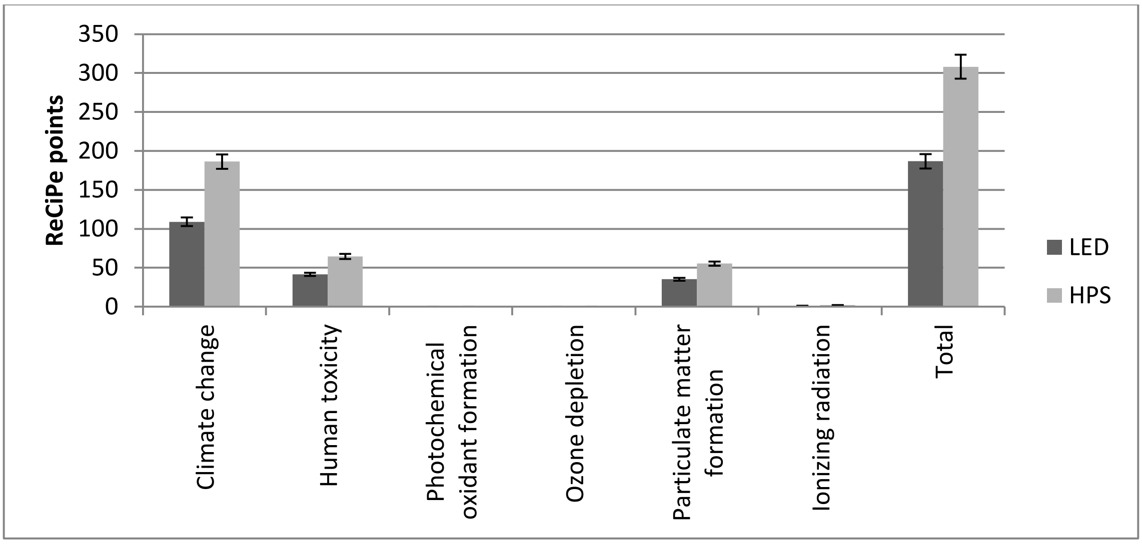

Figure 4.6. Contribution analysis of human health damage category. Chart is using one ton of cucumber seedlings as functional unit.

4.4.2 Evaluation checks

Completeness is the first study quality checked in the second phase of interpretation. A completeness check is conducted by using a checklist with series of questions. Answers to these questions determine the completeness of scope, LCI, or any other LCA element. In this experiment the consistency check has been included in the checklist. The checklist can be found in Appendix D.

Sensitivity check consists of a contribution analysis, uncertainty analysis, and a sensitivity analysis. The contribution analysis in Figure 4.6 includes a section for energy related issues. Therefore, there is no need for a new contribution analysis. An uncertainty analysis has also been performed earlier for the energy use, since the Figure 4.5 dominance analysis chart includes 5 % uncertainty errors in its activities. The difference between energy use in LED and HPS is so great that the 5 % error is insignificant. Sensitivity analysis for the energy use is possible by changing the values in each mode of production systematically. However, it can be assumed that since HPS uses significantly more electricity than LED and both options use the same electricity source, the sensitivity analysis is redundant.

Variation analysis is able to preview the different scenarios of energy use in horticultural lighting. By changing the country where crops are grown, the electricity mix and energy use change as well. Figure 4.7 shows the environmental impacts caused by different unit processes for each country. Data for each country is gathered from the Ecoinvent LCIA database. The energy-related emissions vary between countries due to the different structure of electricity mix in each country. Finland has a balanced electricity mix. Greece, Russia and Germany use a lot of coal and polluting non-renewable energy sources in electricity production. France has an environmentally friendly electricity mix, because majority of its energy is produced by nuclear power plants. Norway has the greenest electricity mix since the main energy source is hydropower.

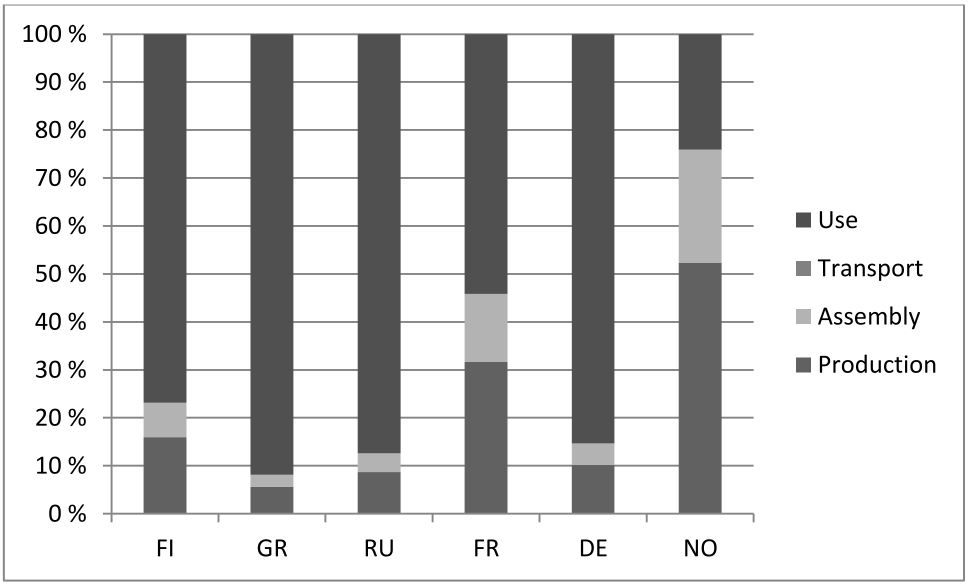

Figure 4.7. Variation analysis by countries with their unique electricity mix.

4.4.3 Conclusions, limitations and recommendations

The LCI spreadsheet tables reveal interesting details about relations between activities. In order to produce one functional unit, a total of 15.29 kg of LED or 15.46 kg of HPS luminaire is consumed in the process. This means that 3 LED luminaires or 2 HPS luminaires are capable of producing at least 1000 kg of cucumber seedlings during their lifetime. However, the number of luminaires required to produce one functional unit is irrelevant. The only aspects that matter are yield and environmental impacts per 1 kg of luminaire.

The LCIA of this experiment clearly shows that the LED scenario is environmentally friendlier in cucumber seedling production than the HPS scenario in every damage category. Human health is the most significant damage category for both luminaires. The damage categories with second and third largest impacts are resources and ecosystem quality respectively. If the results are normalized to average Finnish household electricity usage per year, the production of one functional unit with HPS luminaires causes 81 % and with LED luminaires 49 % of the environmental impacts compared to the reference. Thus, this experiment recommends LED luminaires to be used in horticultural lighting over HPS luminaires at least if environmental aspects are concerned.

The dominance analysis clearly identifies the use phase as the dominant cause for environmental impacts in horticultural lighting. Other lamp and luminaire LCAs have also reached a similar conclusion that the use phase is the dominant cause for environmental impacts [37]. The use phase was expected to be the dominant cause, since the use phase can easily represent more than half of total environmental impacts and over 80 % in some impact categories [10]. This is due to the considerable amount of electricity required to operate a luminaire combined with a long lifespan. The HPS scenario requires nearly double the amount of electricity needed to produce one functional unit than the LED scenario. HPS technology naturally consumes more electricity than LED technology, which has an option to adjust the spectrum specifically for horticulture. Secondary causes for environmental impacts were LED component production and assembly, HPS integrated circuit production, and aluminum parts. The secondary causes were far behind the impact magnitude of the use phase. Most activities such as component production, transports, packaging, and end-of-life have extremely low environmental impacts compared to the electricity use of the luminaires. Recycling has a small positive environmental effect that is allocated to luminaire production.

The contribution analysis is limited to only human health damage category. However, this is acceptable since human health is the most significant damage category. The dominant environmental impact for human health is climate change. The magnitude of climate change is similar to the total environmental effects in resource damage category and almost double compared to ecosystem quality. Human toxicity and particulate matter formation are the next most harmful environmental impacts for human health. Horticultural lighting has almost no effect in photochemical oxidant formation, ozone depletion or ionizing radiation.

The checklist for completeness and consistency check ensures that the elements of LCA are covered correctly. The checklist begins with goal and scope, which were defined clearly and followed accurately. Quality of LCI data, the second section in the checklist, could be improved significantly with bill of material, disassembly and weighing of studied luminaire, and large scale growth experiment. The checklist continues with questions regarding energy, allocation, transports, recycling, LCIA, and reporting. The data for these elements have been provided sufficiently according to goal and scope.

Variation analysis of electricity mix implicates the significance of clean energy sources in electricity production. Changing the source of electricity has the greatest effect in reducing the total damage to ecosystem quality, human health, and resource damage categories. The electricity mix in Finland is listed as the 10th cleanest in the world, which makes Finland a decent candidate for greenhouse growing if environment is concerned according to the Ecoinvent LCIA database. The country with cleanest electricity production mode, Norway, has 69 % lower environmental impacts caused by the use phase compared to Finland. Furthermore, Norway is the only country in the variation analysis with production as the dominant cause for environmental impacts in horticultural lighting.

It is recommended that cucumber seedlings and other crops are grown in a place where the mode of production for electricity is as environmentally friendly as possible. The ideal place to grow crops in terms of environmental friendliness is Norway. However, if cost is the driving force in greenhouse growing then Norway is not the ideal place for crop growing. The cost of other product systems needed to grow crops is huge in Norway even though the electricity cost is relatively low. Electricity price in Finland is one of the lowest in Europe [38]. Thus, Finland strikes a balance between environmental friendliness and cost, making it one of the best places for greenhouse horticulture in northern Europe.

5 Concluding remarks and future aspects

This thesis had two objectives: Firstly, to act as a guide for greenhouse owners and people interested in LCA, and secondly, to reach the goal in the LCA experiment.

The first objective is well addressed. The theory part gives background to horticultural lighting in general. The methods part is vital for the guide, offering tools and framework to conduct any simple LCA. The experiment is an example of how to construct a horticultural lighting LCA using the background provided in theory and methods. The focus in each part is to convey the information clearly and transparently to the reader. This is the most important aspect in a guide and it has been carried out to the letter.

The second objective is also completed successfully. The goal of the LCA experiment was to identify which lighting option, LED or HPS, is environmentally friendlier in cucumber seedling production. The experiment started by defining the elements in goal and scope phase such as product system, data requirements, and assumptions. It continued with the construction of LCI, which includes all the details about data collection and a summary of all flows in the product system. After the LCI phase, the experiment performs the LCIA, where the magnitude of environmental impacts is calculated based on LCI results. Lastly, the results of the experiment are interpreted using various analyses and evaluation checks. The experiment found out that while producing one ton of cucumber seedlings LED luminaires used less electricity than HPS luminaires. The experiment also found out that Finland has beneficial qualities for greenhouse horticulture such as conservative overall environmental impacts and electricity cost. The price of electricity in Finland is low and the electricity mix has relatively low environmental impacts, which makes Finland a favorable place for greenhouse horticulture in northern Europe.

This LCA is first in the field of horticultural lighting and further studies are needed to solidify the findings of this thesis. An interesting goal for further studies would be to identify the best horticultural lighting scenario based on environmental friendliness as well as cost. Such a study would help decision makers and greenhouse owners to choose the best lighting option for growing operations. It is recommended to acquire bills of material and data sheets for all luminaires before the study begins in order to assure the accuracy of the study with as few assumptions as possible. A large scale growth experiment is also important for the credibility of future studies, because results from a computer simulation cannot compare to results from a real growth scenario. Computer simulations contain assumptions, but growth experiments always provide concrete results and as the scale of an experiment increase, so does the reliability of a study.

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Appendix A: Cucumber seedling experiment e-mail attachments

Effect of lighting on cucumber seedling growth over 21 d

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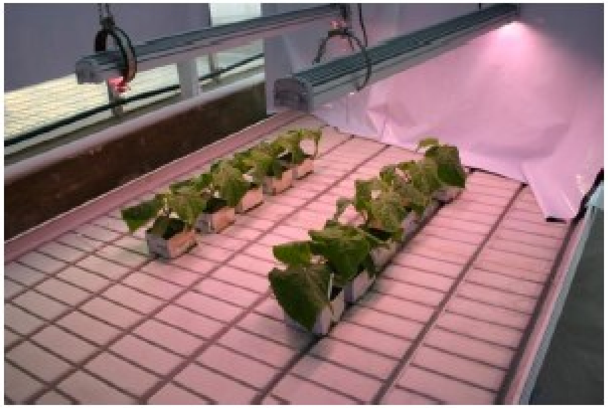
9.7.2013

Experimental protocol

- The aim of the experiment was to compare various artificial lighting treatments in terms of their efficacy on cucumber seedling growth and phytomass accumulation particularly.
- Plants of each treatment were grown in separated compartments in one greenhouse (please see the photos on the next page).
- Compartments of artificial lighting treatments were formed by plastic wall construction to prevent any natural light penetration on the surface of plants. Under natural light treatment sun light was given only.
- Lighting period was 20h / 4 h darkness and temperature (day/night) in the greenhouse was 25 °C / 22 °C.
- Light intensity under each luminaire was 130 µmol m^{-2} s^{-1} except in natural light treatment.
- Plants were fertilized automatically with normal fertigation solution once a day.
- Experiment was started 23.1.2012 and terminated 13.2.2012.
- Fresh and dry weight per plant was determined at the end of the experiment. The results are the means of seven plants per treatment with SE (please see the data on page 5).

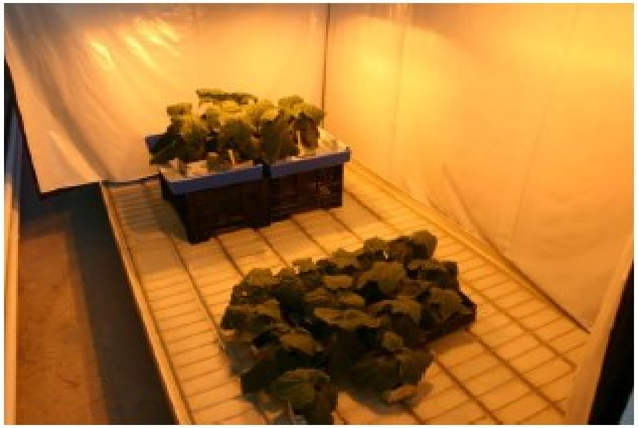
MTT

Experimental setup in a greenhouse



LED 8 [redacted]

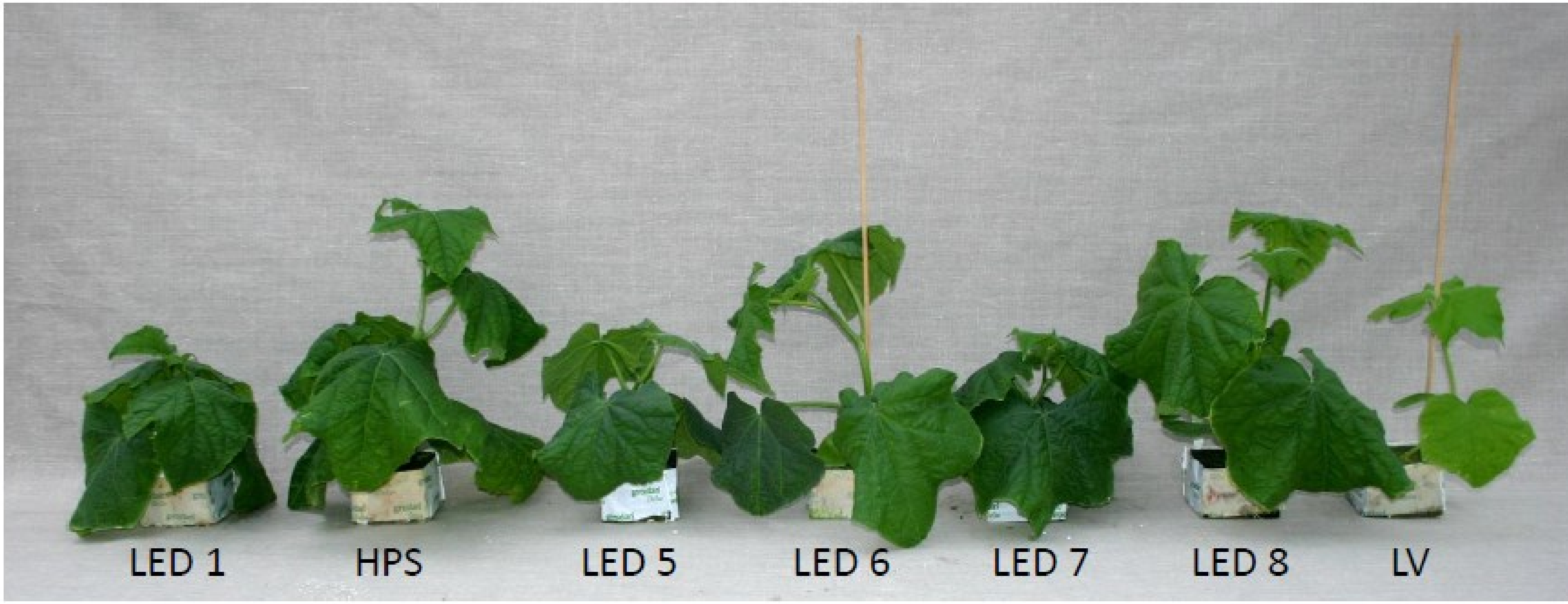
LED 7 [redacted]



High Pressure Sodium (HPS)

Natural light

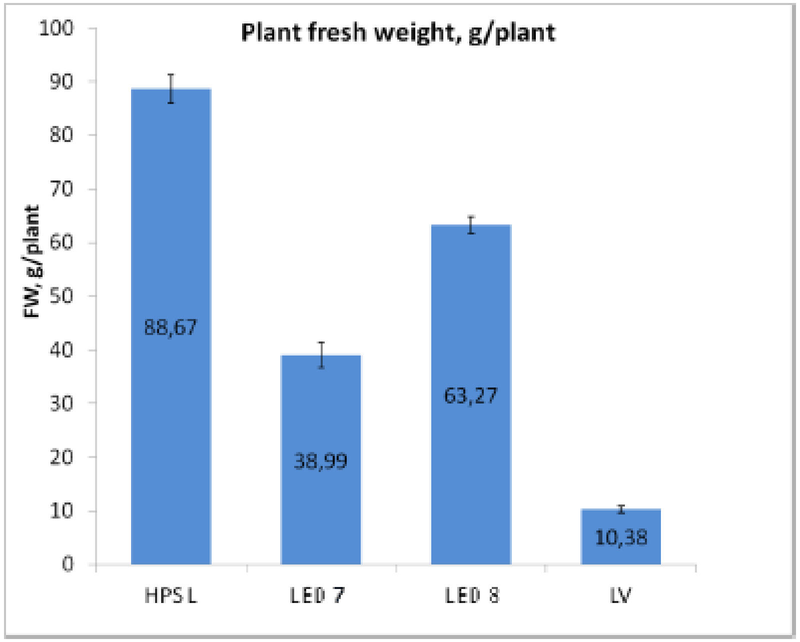
Outlook of cucumber seedling at end of the experiment (21 d)

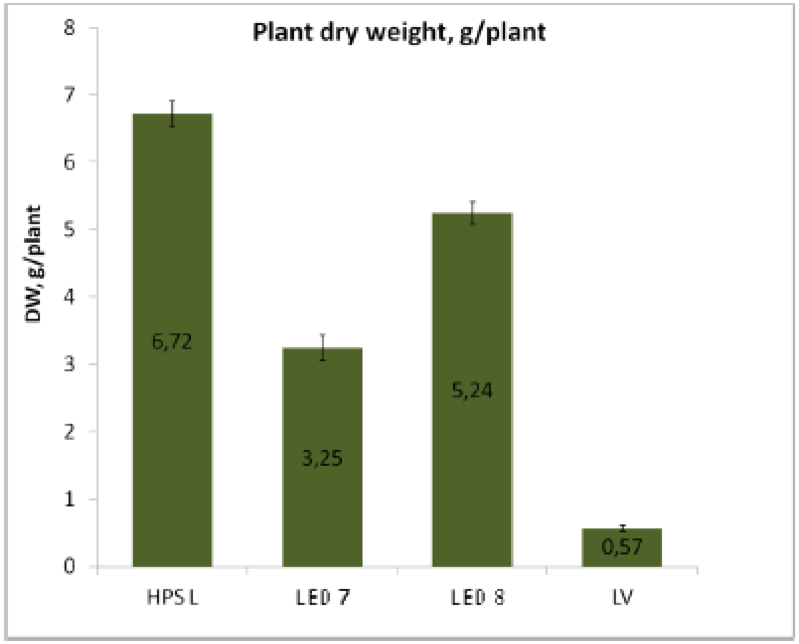


PPFD at the surface of rockwool cube = 130 µmol m^{-2} s^{-1}

HPS= High pressure sodium lamp 250 W
LED 7 = [redacted] Bar
LED 8 = [redacted] Bar
LV = Natural light

Fresh and dry weights of cucumber seedlings at the end of the experiment grown under various luminaires





PPFD at the surface of rockwool cube = 130 µmol m^{-2} s^{-1}

Appendix B: Inventory for the LED luminaire

Unit process	Part	Details	Unit	Reference	Multiplier	Amount
Production	Ballast	Rigid foam	g	3	2,57	7,7
Production	Ballast	Inductor	g	6	2,57	15,4
Production	Ballast	Inductor	g	4	2,57	10,3
Production	Ballast	Zener diodes	g	0,1	2,57	0,3
Production	Ballast	Capacitors	g	5	2,57	12,9
Production	Ballast	Resistors	g	10	2,57	25,7
Production	Ballast	Transistors	g	3	2,57	7,7
Production	Ballast	Aluminum block (PCB)	g	200	2,57	514,5
Production	Ballast	Wiring	g	2	2,57	5,1
Production	Ballast	Sn95.5Ag3.9Cu0.6	g	1	2,57	2,6
Production	Ballast	Housing	g	35	2,57	90,0
Production	Ballast	Integrated circuit	g	1	2,57	2,6
Production	Ballast	PET Film	g	2	2,57	5,1
Production	Fitting	Aluminum parts	g	100	55,34	5534,0
Production	Fitting	Metal clips	g	30	2,81	84,4
Production	Fitting	Wiring	g	10	2,81	28,1
Production	Lamp	Pins	g	0,1	2,81	0,3
Production	Lamp	Base contacts	g	0,4	2,81	1,1
Production	Lamp	Sn95.5Ag3.9Cu0.6	g	0,2	2,81	0,6
Production	Lamp	2 Watt LED	g	30	2,81	84,4
Production	Lens	Glass tube	g	30	2,81	84,4
Production	Lens	Coating	g	1	2,81	2,8
Production	Packaging	Corrugated cardboard	g	3		200,0
Assembly	Lamp	Luminaire assembly	g	31		86,3
Transport	Luminaire	Transoceanic freight ship	tkm	9,82		9,82
Transport	Luminaire	Truck, 200km 16-32ton	tkm	0,1		0,1
Use	Luminaire	Electricity mix (FI)	kWh			3566,5
Recycling	Luminaire	Electronic scrap	g	410		3260
Recycling	Luminaire	Corrugated cardboard	g	2		100
Disposal	Luminaire	Electronic scrap	g	102		3260
Disposal	Luminaire	Corrugated cardboard	g	1		100

Appendix C: Inventory for the HPS luminaire

Unit process	Part	Details	Unit	Reference	Multiplier	Amount
Production	Ballast	Rigid foam	g	3,0	4,04	12,1
Production	Ballast	Inductor	g	6,0	4,04	24,3
Production	Ballast	Inductor	g	4,0	4,04	16,2
Production	Ballast	Zener diodes	g	0,1	4,04	0,4
Production	Ballast	Capacitors	g	5,0	4,04	20,2
Production	Ballast	Resistors	g	10,0	4,04	40,4
Production	Ballast	Transistors	g	3,0	4,04	12,1
Production	Ballast	Aluminum block (PCB)	g	200,0	4,04	808,5
Production	Ballast	Wiring	g	2,0	4,04	8,1
Production	Ballast	Sn95.5Ag3.9Cu0.6	g	1,0	4,04	4,0
Production	Ballast	Housing	g	35,0	4,04	141,5
Production	Ballast	Integrated circuit	g	1,0	4,04	4,0
Production	Ballast	PET Film	g	2,0	4,04	8,1
Production	Fitting	Ceramic bulb holder	g	176,9	1,00	176,9
Production	Fitting	Weather guard	g	10,2	1,00	10,2
Production	Fitting	Black plastic insulator	g	73,9	1,00	73,9
Production	Fitting	Photocell cap	g	24,4	1,00	24,4
Production	Fitting	Photocell plastic	g	11,3	1,00	11,3
Production	Fitting	Photocell plugin	g	45,3	1,00	45,3
Production	Fitting	Wiring	g	60,0	1,00	60,0
Production	Fitting	Aluminum parts	g	4376,0	2,01	8792,4
Production	Lamp	Circuit board	g	40,8	2,00	81,6
Production	Lamp	Circuit board copper	g	5,1	2,00	10,2
Production	Lamp	Felt heat shied	g	2,9	2,00	5,7
Production	Lamp	Paper insulator	g	1,3	2,00	2,5
Production	Lamp	Plastic circuit board	g	22,8	2,00	45,5
Production	Lamp	Big capacitor	g	220,9	2,00	441,8
Production	Lamp	Circuit board capacitor	g	7,1	2,00	14,3
Production	Lamp	Diode	g	0,4	2,00	0,9
Production	Lens	Light bulb	g	114,4	2,00	228,8
Production	Packaging	Corrugated cardboard	g			300,0
Assembly	Lamp	Luminaire assembly	g			60,2
Transport	Luminaire	Transoceanic freight ship	tkm			15,9
Transport	Luminaire	Truck, 200km 16-32ton	tkm			0,2
Use	Luminaire	Electricity mix (FI)	kWh			11666,7
Recycling	Luminaire	Electronic scrap	g			5562,8
Recycling	Luminaire	Corrugated cardboard	g			150,0
Disposal	Luminaire	Electronic scrap	g			5562,8
Disposal	Luminaire	Corrugated cardboard	g			150,0

Appendix D: Checklist for completeness analysis

Goals

Q: Are the goals of the study well defined?

A: Yes. The goal is to identify which technology, LED or HPS, is environmentally friendlier in cucumber seedling production.

Scope

Q: Is the function and functional unit clearly stated?

A: Yes. The function of horticultural lighting is to produce crops. The f.u. is 1000 kg of cucumber seedlings.

Q: Are comparative systems functionally equivalent?

A: Yes. The HPS and LED systems are comparable.

Q: Is the system boundary clear (cradle-to-grave or -gate etc.)?

A: Yes. Cradle-to-grave.

Q: Is the scope of data and impact categories consistent with the study goals?

A: Yes.

Quality of life cycle inventory (LCI) data

Q: Are the data based on achieved and measured performance? If not, are the assumptions realistic?

A: The data for growth experiment is measured. The data for luminaires is mainly from other LCAs. The missing data is assumed realistically.

Q: Are the data relevant in terms of time, location and technology?

A: Somewhat. The data is fairly recent. The luminaire manufacturing location is modeled as global even though it is China. The technology for luminaires is few years outdated.

Energy

Q: Is primary energy (i.e., extracted from the earth) used and are the different energy sources clearly defined?

A: Partly. Only the mode of production has been clearly defined for the Finnish electricity mix.

Q: What assumptions are made for electric power generation?

A: Power is generated in the country where luminaires are used.

Q: Are the production, delivery, fuel and feedstock energies included?

A: Yes.

Allocation for co-products

Q: Are the rules for allocation stated and has the stepwise procedure been applied?

A: A simple allocation procedure has been stated and applied.

Transport

Q: Have significant transport steps been included and are the means of transport and distances realistic?

A: Yes.

Recycling

Q: Does the study take account of recycling and is the methodology for credits appropriate?

A: Recycling is accounted for and the ReCiPe methodology is appropriate.

Q: Are the recycling process stages included and are recycling rates derived from actual data?

A: No.

Q: If not are the assumptions realistic?

A: No. The probable scenario for recycle/waste is 10/90.

Life cycle impact assessment

Q: What impact categories are considered and is the LCI scope consistent with this?

A: Every impact category in ReCiPe.

Q: Are the impact assessment methods technically valid and internationally accepted?

A: Yes. ReCiPe is an internationally accepted LCIA methodology.

Q: Have value choices (e.g., weightings) been used and on what basis?

A: Yes. The 1 Watt LED has been weighed with a factor of 5, because the database has not got data for 2 Watt LED.

Reporting

Q: Is a methodology report available to third parties?

A: Yes.

Q: Is the report transparent and clear regarding the methods and data used?

A: Yes.

Q: Are the LCI results also available where impact assessment is applied?

A: Yes.